RE-SURFACE:
The Novel Use of Deployable and Actively-Bent Gridshells as Reusable, Reconfigurable and Intuitive Concrete Shell Formwork

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"Imagination is more important than knowledge.

Knowledge is limited, but imagination encircles the world."

Albert Einstein

“any development that saves money and effort in construction contributes more to the general well-being of mankind than all the messianic claims so common in the profession”

Felix Candela (in Faber, 1963)

Declaration:

I declare that this thesis is an original report of my research, has been written by me and has not been submitted for any previous degree. The experimental work is almost entirely my own work; the collaborative contributions have been indicated clearly and acknowledged. Due references have been provided on all supporting literatures and resources.

I declare that this thesis was composed by myself, that the work contained herein is my own except where explicitly stated otherwise in the text, and that this work has not been submitted for any other degree or professional qualification.

Gabriel Jin-Peng Tang

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I would like to thank my family for their steadfast support and selfless act of sending me on this journey of intellectual discovery. I thank Ken Smith for all his helpful support over the years. To my god-family, I am grateful for all your prayers and spiritual encouragement.

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Abstract

RESURFACE: The Novel Use of Deployable and Actively-Bent Gridshells as Reusable and Reconfigurable Concrete Shell Formwork

Following a well-documented rise in the popularity of concrete shell application in the 20th century, thin concrete shells have experienced a global decline despite their potential as efficient structures with an economy of material use with aesthetics benefits.

This phenomenon is subject to geographically determined socio-economic conditions and competition from other building solutions as a result of technological advancement in alternative construction systems. Importantly, their decline was attributed to limitations inherent to concrete shell formwork and construction methods. Being able to produce efficient shaping did not ensure that this method of construction is most cost efficient as it still remains difficult to construct double curved surfaces.

The thesis addresses the limitations associated with past and present concrete shell building by proposing the use of actively-bent gridshells as re-configurable and reusable formwork for concrete shells to be designed and built.

The hypothesis uses deployable scissor-jointed actively-bent gridshells as re-configurable and reusable formwork for concrete shell construction. This was developed from a series of Flash research (Benjamin, 2012) as student construction workshops to investigate the design and creation of actively-bent gridshells held between December 2008 and March 2011 in Sheffield.

In this study, to understand this new system, scaled models of actively-bent gridshells were used as preliminary design aid. Deployed into three dimensional forms from a flexible flat grid mat, the structures were rigidized by bracing through triangulation restraints. The temporary rigid structure was subsequently enveloped with fabric onto which concrete was applied to create the concrete shell, thus acting as formwork. This formwork was then removed following the curing of the concrete cast to be reused repeatedly, or reconfigured into another concrete shell form.

Hence, the thesis draws on the concepts, principles and ideas pertaining to three key architectural technologies: 1. concrete shell, 2. actively-bent gridshells and 3.fabric formwork.

The thesis then presents a series of four prototype concrete shells constructed from different materials spanning between 1.3 meters and 2.45 meters in the workshops at the University of Edinburgh built between August 2014 and September 2015.

For each experimental construction, the process of gridshell construction, fabric formwork preparation, concrete casting, gridshell formwork decentring and different design elements of openings, edges and

anchorage abutments were analysed and discussed under the themes of construction, architectural tectonics and structure. The tectonic of process and material is understood and discussed based on the idea of stereogeneity (Manelius, 2012). Specifically, the relationship between gridshell as formwork and the concreting process was studied, analysed and assimilated in concrete shells built with progressive sophistication and elegance, culminating in a doubly-curved concrete shell that demonstrated both synclastic and anticlastic geometries, with further abutment simplification, edge leaning and physical openings incorporation.

The study concludes with a physical concrete shell model formed by applying concrete onto fabric formwork to cover the Weald and Downland Jerwood gridshell. In the 1:20 scaled model, the proposed method is speculatively applied onto fabric stretched between pre-determined curvatures of the as-built gridshell. This formwork was subsequently removed for reuse, re-deployed and reconfigured. Using finite element analysis, the structural behaviour of the gridshell made of glass-fibre reinforced tubes and structural characteristics of the resultant concrete shell was checked. The interaction between the three technologies are discussed architectonically and structurally to inform guidelines for potential life-scale application.

The thesis evidences the feasibility of the proposed system. It re-purposes a scaled model of a deployable gridshell as a physical modelling tool to facilitate concrete shell design, for both pure compression shells and "improper" shells, demonstrating its adaptability. It also promotes and reinvigorates concrete shells as possible architectural systems serving to instigate future research to revive concrete shell construction as an intelligent and intuitive way of creating structures with material economy, structural efficiency and visual elegance.

List of Key Publications

Listed below is a selection of relevant publications to date:

Monograph

Chilton, John and Tang, Gabriel, 2017
Timber Gridshells: Architecture, Structure and Craft, Routledge 2017

Journal Papers

TANG, Gabriel, 2015 (in press) An Overview of Historical and Contemporary Concrete Shells, their Construction and Factors in their General Disappearance ;International Journal of Space Structures May 11, 2015 International Journal of Space Structures Vol. 30 No. 1 2015 Print ISSN: 0266-3511

TANG, Gabriel, 2013. (in press) Timber Gridshells: Beyond the Drawing Board. Proceedings of the Institution of Civil Engineers. Construction Materials, 166 (6), 390-402. Paper reporting the research outcome of a 2011 construction workshop held at Sheffield Hallam University.

Conference Papers

Veenendaal D, Augustynowicz E and Tang G, 2017
Magnolia: a glass-fibre reinforced polymer gridshell with a novel pattern and deployment concept
IASS (International Association of Shells and Spatial Structures)
Interfaces: 23rd- 25thSeptember 2017 Hamburg, Germany

TANG, Gabriel, 2016 Structural Intuition and Creative Play: An Architectural Perspective to Shell Pedagogies. (in press) International Association of Shell and Spatial Structures Annual Conference September, 2016. Tokyo, Japan.

TANG, G. & PEDRESCHI, R, 2015 (presented and in press) Deployable Gridshells as Formwork for Concrete Shells. ICFF Conference Proceedings of the International Society of Flexible Formwork (ISOFF) Symposium, 2015, Amsterdam, The Netherlands 16 - 17 August 2015
TANG, Gabriel, 2014. (in press). The Birth of Shell Forms without Computers
– A Student Construction Workshop Shells, Membranes and Spatial Footprints.
IASS/SLTE 2014 Proceedings, Brasilia, Brazil 15-19th September 2014 (Printed Proceedings)

TANG G., Chilton J. and Beccarelli P., 2013. (in press) Progressive Development of Timber Gridshell Design, Analysis and Construction: Paper 1387 In: Proceedings of International Association for Shell and Spatial Structures (IASS) Symposium 2013, 23-27 September, Wroclaw University of Technology, Poland, J.B. Obrębski and R. Tarczewski (eds.). 6

TANG, Gabriel. (presented and in press) Gridshells and their application as temporary, reusable and flexible Concrete Formwork. Proceedings of ICFF (International Conference on Flexible Formwork) Conference, University of Bath, UK, June 2012

TANG, Gabriel., 2012 (presented and in press) The Rise and Fall of The Thin Concrete Shell – Form Active structures and its relationship to Formwork Proceedings of ICFF (International Conference on Flexible Formwork) Conference, University of Bath, UK, June 2012

TANG, Gabriel, 2012 (presented and in press) Deployable Gridshells and their application as a Physical Form Finding Tool: Constructing an innovative life-size Strained Timber Gridshell Proceedings of IASS (International Association of Shells and Spatial Structures) Conference From Spatial Structures to Space Structures, Seoul, South Korea, 23rd May 2012

POPOVIC Larsen O, TANG G, LEE D, 2010. Innovative Spatial Timber structures: workshops with physical modelling explorations from small to full scale. Proceedings of The International association for Shell and Spatial Structures (IASS) Symposium 2010, Shanghai, China. Spatial Structures- Permanent and Temporary November 8-12, 2010

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PART 1 THE BASIS OF RESEARCH

Chapter 1 INTRODUCTION

Chapter 1: Introduction

1.1 Context: Concrete Shells in the 21st Century

Concrete shells can be beautiful, efficient and economical structures. Since the construction of engineered thin concrete shell of Jena Planetarium in 1922 with its platonic spherical geometry, widely recognised to be the first, shell designers have striven to simplify and improve design and construction of concrete shells, with varying degree of success. The ambition to simplify and economise concrete shell construction methods (materially and cost-wise), and design beautiful shells with increasingly complex geometries, motivated this search of a method of building shells cheaply and quickly. Although concrete shells can be strong and beautiful, whilst using very little concrete, their design and formwork preparation remains extensive and expensive.

Concrete shells are built with very little material (concrete and reinforcements) and are capable of impressive span to thickness ratio of 367:1 (Cosmic Ray Pavilion 1951 by Felix Candela). Through their doubly-curved forms, they can provide clear spans without intermediate support, useful for spaces requiring clear sight-lines such as concert venues, sports stadia and churches. Their doubly-curved forms can also help craft the feeling of light and space to create great architectural interest.

Despite concrete's reputation being sustainably unsound, their exposed surfaces, increasingly accepted as an architectural finish, offer thermal mass for the spaces it defines.

With so many attributes to concrete shell's credit, the current state of concrete shell activity remains low with recent examples by SANAA at Teshima Island (2010). Paradoxically, they are no longer built as much as they had been in the past. This follows a well-documented rise in the popularity of concrete shells in early 20th century which saw thin concrete shells experiencing an eventual decline despite their potential as efficient structures with material economy and aesthetics benefits.

This observation therefore asks an intriguing question: Why are they not built anymore? What is the relationship between concrete shells and formwork and construction technologies? Could current construction of double-curved forms be used or be re-purposed as temporary concrete shell formwork to erode associated shortcomings of current concrete shell techniques and material?

1.2 Problem

This intriguing question revolves around why such structures which offer efficiency, economy and aesthetics values are not built as much as they were in their heyday in the 50s and 60s. By examining the factors that led to this decline, elements of shell design could be addressed. Through tackling these shortcomings, a new method and system of construction could perhaps revive concrete shells.

1.2.1 Socio-economic drivers and inhibitors for concrete shell typology

Examining the problem, this decline is partly due to geographically-determined socio-economic conditions as well as competition from other structural construction systems. The low cost of labour in certain economies and the availability of concrete at a very specific time after world wars, helped maintained their popularity in countries like Mexico. These issues will be presented and discussed in detail in Chapter 3.

They were popular in the past, especially before and during the world wars as it was possible to construct clear, large spanning buildings used quickly and efficiently, as Nervi spectacularly demonstrated in the Orvieto aircraft hangars in the 1930s and 1940s (Chapter 3.3.5). The shortage of steel, otherwise employed in artilleries and the readily availability of cheap labour during also saw the growing popularity of concrete becoming a shell material in Europe. In the Americas and Europe, during the post-war period, the possibilities of concrete to create curved structures (and not necessarily proper shells) came to represent the optimism and hope that propelled the popularity of concrete shells as an architectural solution.

Importantly, history attributes their eventual decline to limitations inherent to societal acceptance as temporal architectural fashion (Cassinello, Schlaich and Torroja, 2010). This decline can also be traced to them losing out to competitor structural solutions such as steel and concrete frames which offered better spanning potential, increased construction speed and accuracy, and with adaptability for future design changes, not offered by shells of concrete (as in chapter 3.4.10).

1.2.2 Design difficulties

Concrete shells were difficult to design. Proper shells (acting largely in compression) require an understanding of force and form, in addition to satisfying the requirement for the spatial design. In the past, structural design of shells involved complex analysis of differentiation to 4th degree partial differentiation. With digital advancement, shell forms can be form-found and analysed using powerful analysis software. However, these design tools are specialised and not as user-friendly or as assessible, leading to the designer discounting shells as a viable and economical architectural solution. Current design methods are not user-friendly and intuitive to the needs of the designer.

1.2.3 Construction (Formwork) Challenges

Compared with other structural systems, thin concrete shells are traditionally formwork- and labour-intensive, demanding a sound technical understanding of formwork construction, concrete casting and de-centring (formwork removal). Hence, to design concrete shells well, material behaviour and system assembly understanding (i.e. concrete and formwork construction) is expected. Closely linked to formwork systems, a working understanding and an experience of formwork design is vital. Consequently, concrete shell design and construction demands a holistic understanding of material properties and manipulation/process of both concrete and formwork.

Difficulties in formwork, their design methods and associated construction techniques caused their decline. This is partly linked to difficulties associated with designing and constructing double-curved structures and surfaces, something shell designers have tried to perfect since the beginning of the 20th century. Examples include rigid systems as well as soft/ flexible types discussed presented in chapter 3.6. Interestingly, great strides were made in technology terms, seen in the contemporary research at TU Vienna on pneumatic wedge system (chapter 3.7.3.4.2) and at ETH on the use of cable nets as concrete shell formworks (Chapter 3.7.3.4.4), to unveil the perennial shortcomings of shell construction techniques - namely, the lack of construction ease, limiting one-off form expression and the system not being reconfigurable/ re-useable and involving cumbersome formwork erection sequence/ procedure.

As such, the search continues for a singular system that is capable of eroding current shortcomings i.e. a system that is re-useable, re-configurable but was also easy to use for their preliminary design and in understanding their construction.

1.3 Response: The Deployable Gridshell

Through parallel research on timber gridshells (chapter 5.5), and a series of student construction workshop projects (chapter 5.6), deployable gridshells are encountered to embody the qualities of a structural formwork system that address problems identified with current shell system shortcomings: to address the fact that they are not re-usable, and/or reconfigurable, and/ or not intuitive to the designer.

1.3.1 Re-useable

Using bending-active materials (such as glass fibre reinforced plastic tubes) with a suitable elastic modulus, the assembled gridshell gridmat becomes readily reusable. The availability of the gridmat to form either the same (but repeated) or completely different double curvatures readily address the issue that current shell formwork are unsustainably bespoke to each concrete shell project.

Although these concrete shell casting may be cheap and quick to manufacture (largely through digital technology and fabrication techniques), they still could only be used once, remaining unsustainable unless re-used for the repeated casting of the same geometry. As such, re-usability demand implies a sustainable and cost-effective solution with cost of casting being inversely proportional to casting use (as discussed in Chapter 6.2.3).

1.3.2 Re-configurable

Gridshell gridmats are reconfigurable in terms of shell expression as the same gridmat is capable of creating (both proper and improper) shells of different shapes. Gridmats can also be extended by joining different mats together, or contracted by removing different mats. These gridmats can be made into gridshells of different sizes and geometries (discussed in Chapter 6.2.4).

1.3.3 Intuitive Design

Deployable gridshells are re-organising and re-adjustable structures whose forms are responsive to applied forces. Although, sophisticated and specialised digital tools and softwares are available, the use of scaled physical gridshell models help designers understand the impacts of double-curved shaping in tune with applied forces readily (demonstrated in Chapter 6.3). They allow the designer to work with shells, even at a preliminary stage of the design. This encourages an intuition and understanding of relationship between force and form not offered by current digital methods of designing shells. Importantly, this invites designers to consider shell structures, rather than be deterred by the time and difficulties of designing them.

1.4 Aim:

Specifically, the research aims to answer the question of whether the use of scissor-joint deployable and actively-bent gridshells as re-usable and re-configurable temporary formwork for constructing concrete shells is possible. As the proposed technology also involves the use of fabric as formwork stretched across the deployed gridshell, this innovative method combines existing technologies into a hybridised technology with a unique aesthetic expression.

This idea is tested through constructing a series of progressively sophisticated physical concrete shell tests. Issues associated with each prototype construction are recorded and analysed to address past challenges faced by concrete shells. Through hands-on constructions, the interaction between actively-bent gridshell formwork and concrete is analysed and improved. The resultant concrete shells were subsequently checked by structural engineers to evaluate their structural properties.

1.5 Objectives:

The thesis examines how technological advances, social-economic factors (external and internal inherent factors) have led to the rise and fall of concrete shells. Internal factors relate to technical aspects of the design and construction of concrete shells whilst external factors are defined as society's acceptance of concrete shells as architectural solutions. By first examining issues and challenges associated with thin concrete shell forming and construction methods, the line of inquiry is shaped by these observations and identified shortcomings.

Therefore, this novel method is devised to erode these shortcomings or "internal factors". To test this novel idea, a series of four concrete shells were constructed. For each test shell, system and method were critically analysed and evaluated. The resultant concrete shell structures were analysed specifically in three aspects: construction, aesthetic and structure, the last aspect will be done with help and guidance from MEng students and engineering colleagues.

This idea then culminated in the construction of a 1:20 scaled version of a concrete shell by using a deployable and re-configurable glass fibre reinforced plastic formwork system that replicated the efficiently form-found Weald and Downland gridshell. This test exercise was also analysed in terms of construction, aesthetic and structure.

Hence, the research discusses, assesses and evaluates the viability of this novel idea to fill a gap in the technological thinking and link between deployable and actively-bent gridshells and thin concrete shells.

1.6 Approaches

1.6.1 Flash Research: Finding the research Question

The hypothesis was the result of a series of spontaneous Flash Research (Benjamin 2012), carried out through student workshops to investigate the design and building of actively-bent gridshells. Primarily, these "blue-sky", explorative construction exercises explored particular aspects without prejudiced views or pre-conceived outcomes. Flash research can therefore be seen as an explorative methodology to understand an aspect of research area, characterised by a short time-frame and with a limited budget (Benjamin, 2012) which will be discussed in detail in Chapter 6.6.

Flash research is therefore imperative to the hypothesis. It is only through these experimental workshops that the potential of deployable gridshells as re-usable, re-configurable and intuitive formwork was uncovered and the research question surfaced.

1.6.2 Prototyping: Testing and evaluating the idea

With the research question defined, a series of prototypes or test shells were constructed to explore particular aspects of the proposed system describe in detail in chapter 6.9.

Through proposing the use of actively-bent gridshells to aid concrete shell design and constructions, the hypothesis uses deployable scissor-jointed actively-bent gridshells as formwork to address identified formwork issues (Chapters 7, 8 and 9). Observations and findings of four concrete shells using different materials spanning between 1.3 meters and 2.45 meters constructed in the workshops at the University of Edinburgh built between August 2014 and September 2015. For each experimental construction, the process of gridshell construction, fabric formwork preparation, concrete casting, gridshell formwork decentring and different design elements of openings, edges and anchorage abutments were analysed and discussed under the themes of construction, architectural tectonics and structure.

Admittedly, prototypes are limited in terms of scale and accuracy. Therefore, this concludes with the construction of a 1:20 scaled physical concrete shell model (Chapter 10) formed using the 2002 Weald and Downland Jerwood gridshell as formwork. To verify the structural performance of the shell, finite element analysis, the structural behaviour of the gridshell (of glass reinforced plastic rather than timber) and the resultant concrete shell were checked. The interaction between gridshell, fabric formwork and eventual shell is discussed architectonically and structurally presented to inform guidelines of potential life-scale application.

1.7 A Chronology of Research Tasks

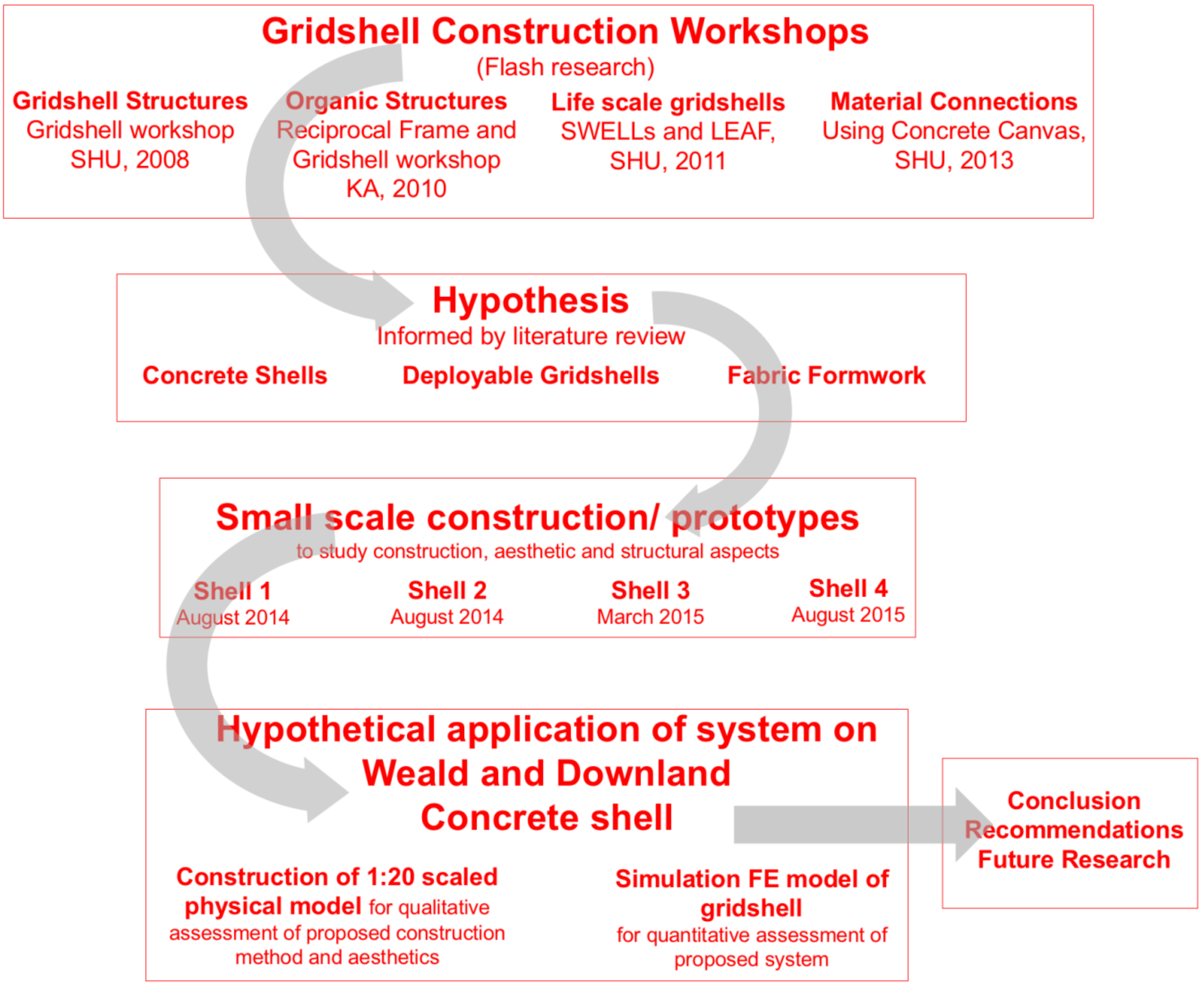


Fig 1.1 "Road Map" of the PhD that shows a chronology of key events and activities that informed the PhD research.

With reference to fig 1.1 above: Construction of deployable gridshells is explored, firstly through a series of Flash Research on gridshell construction with students within Sheffield and abroad. The format was inspired from a series of student construction workshops where construction of gridshells and other light-weight construction systems were experimented. The challenges faced by initial timber gridshell constructed led to the re-configuration of this system. The concept of using gridshell as formwork as the culmination of three technologies were thoroughly researched as literature review to understand the behaviour of these technologies but also provide a cultural, social and economic context to why these structures are no longer constructed as much as they were in the past. This led to four prototyping studies and laboratory construction to understand and study the interaction of the system. Subsequently, an imaginary scenario of applying this technology to the Downland gridshell constructed from GFRP tubes is studied. To understand the construction process and appreciate the architectural results, a physical 1:20 scaled model was constructed. Finite element model simulations carried out on this imaginary scenario is used to further understand and validate this technology.

1.8 Thesis Structure and Chaptering

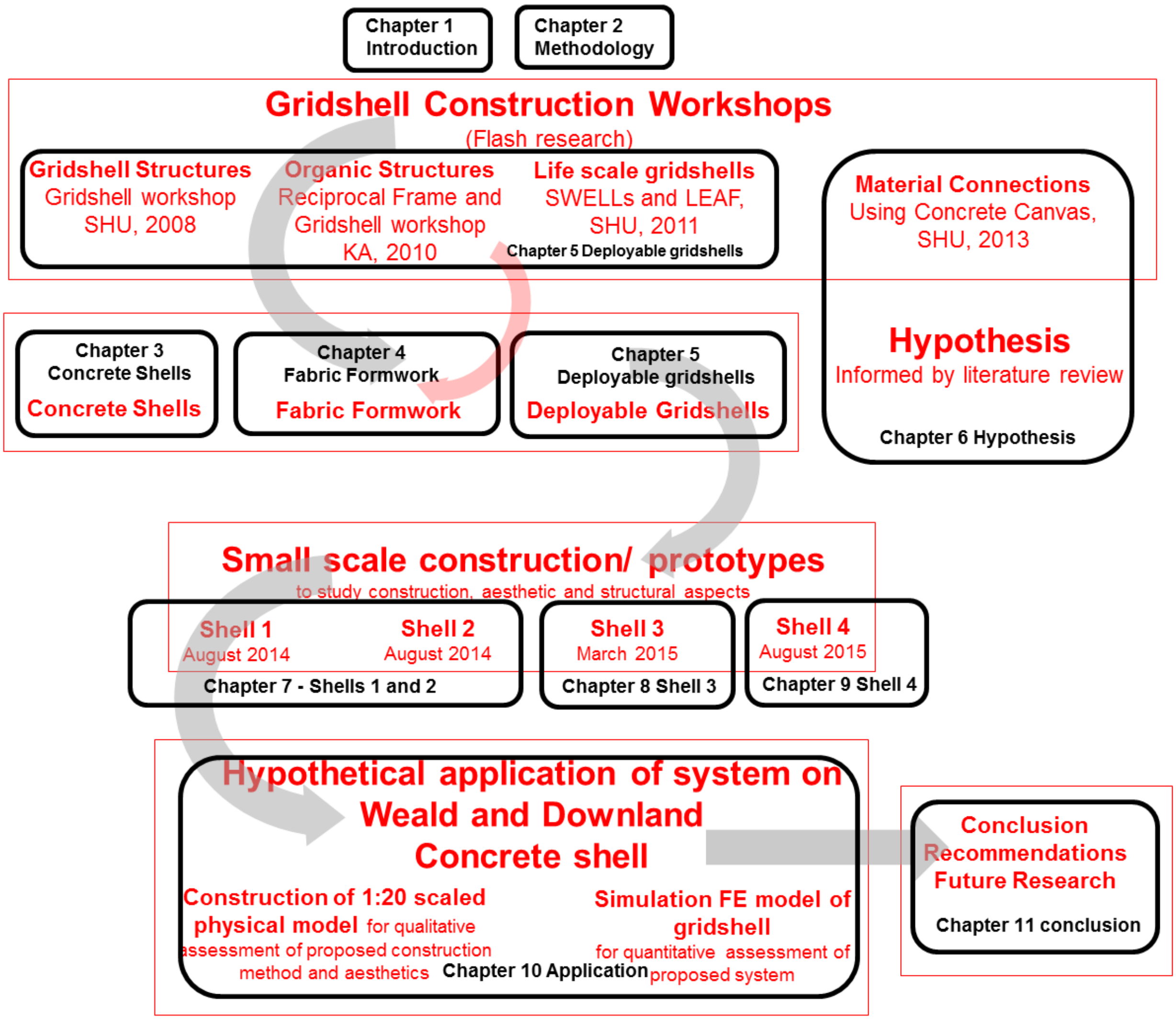


Fig. 1.2: A systematic line of inquiry is covered by various chapters structuring.

The chronology of the research programme is arranged and structured to present ideas in a logical fashion.

Referring to Fig 1.2 above, Chapter 1 introduces the thesis, whilst Chapter 2 describes the methodology employed. The research started from a series of Flash Research workshops on gridshell construction. This is presented and discussed with deployable gridshells in chapter 5. A background to the constituent technologies is covered in chapter 3 (concrete shells), 4 (fabric formworks) and 5 (deployable gridshells). Chapter 6 explains the hypothesis, informed by the literature review forms the bases of research questions. Following on from the definition of the research question informed by the literature review, a series of prototypes were built to test these specific aspects. Each section is analysed in terms of process (gridshell formwork movement), aesthetics (appearance) and structure (concrete shell strength). The research work then concludes with the construction of a 1:20 scaled model of the Weald and Downland concrete shell with analysis structured again under the three sub-headings of construction, aesthetics and structures (with structural analysis help from ARUP engineers).

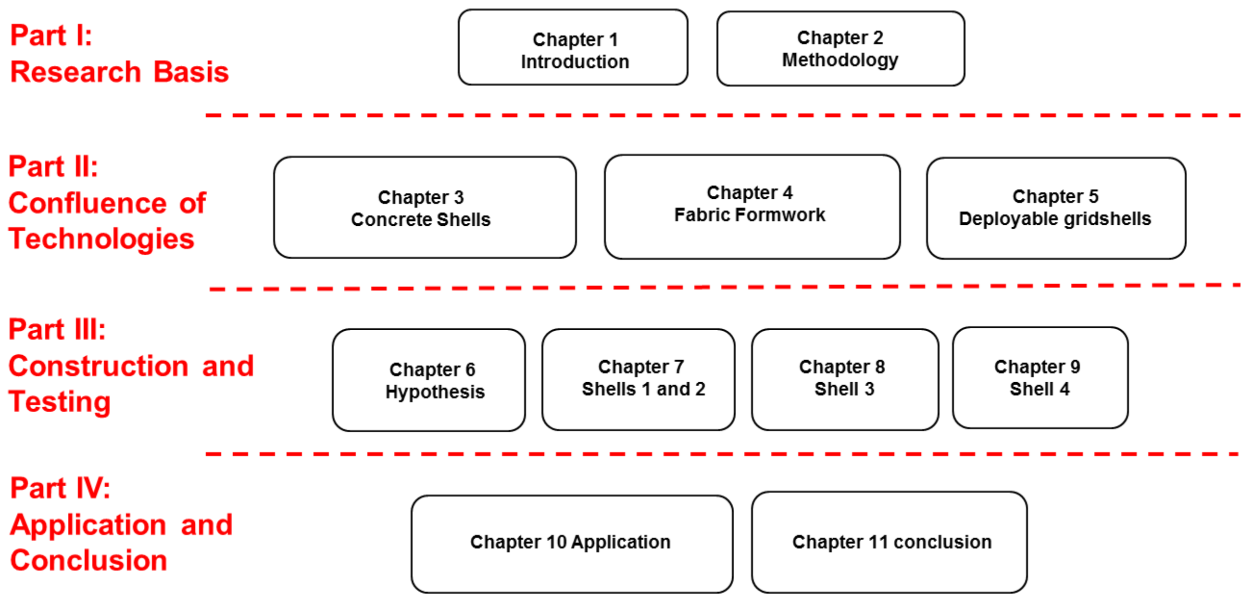


Fig. 1.3: Thesis is partitioned into four parts: Part I: Research Basis, Part II: Confluence of the three technologies, Part III: Construction and Testing: Hypothesis and the four experimental testing. Part IV describes the speculative application of this technology onto a pre-standing gridshell building.

For ease of navigating through this presentation of this body of work, the thesis is arranged into 4 parts as graphically described in fig. 1.3.

Part I discusses the Research Basis which includes two chapters namely, the Introduction, and thesis methodology.

Part II is entitled the Confluence of Technologies provides an overview and literature reviews of the three constituent technological themes namely deployable gridshells, fabric formworks and concrete shells.

Part III (Constructing and Testing) begins with the hypothesis, combines the three technologies and speculates their use and establishes the method novelty. Building on this conceptual basis, chapters 7, 8 and 9 state the aim of each construction and through physical constructions, tests and analyse each individual test and test result (concrete shell) in terms of process, aesthetic and structural performance.

The final section, Part IV concludes the study with the hypothetical application of this technology through model construction of a concrete shell Downland gridshell achieved through modelling a 1:20

scale physical model. Chapter 11 concludes this PhD study drawing on the main findings to suggest limitations and further research avenues.

The following chapter will describe the methodology in more detail.

Interior, Church of Our Lady of the Miraculous Medal, Mexico City, Felix Candela (1953- 1955) 2016 (Gabriel Tang)

PART 1 THE BASIS OF RESEARCH

Chapter 2 METHODOLOGY

Chapter 2: Methodology

Research Methodology

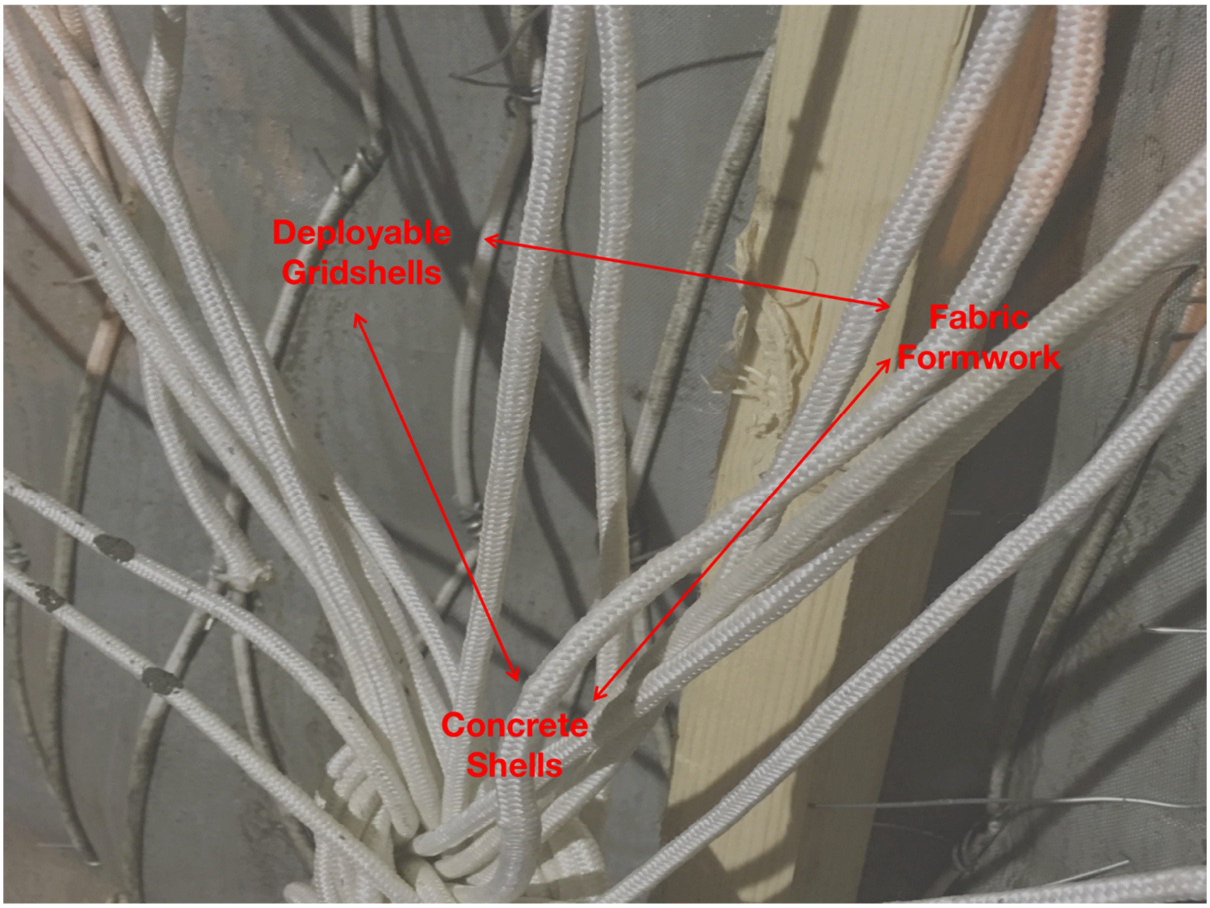


Fig 2.1 Technology Strands : Concrete shells, Fabric Formwork and Deployable Gridshells

A Tale of Three Technologies

This PhD research synthesises three technological concepts: that of concrete shells, fabric formwork and deployable gridshells. This research was sparked by a series of "blue-sky" / *dérive* construction exercises on gridshells with students. Subsequently, it converged into an enquiry with specific focus. This research therefore expects an understanding of each technology and an appreciation of their interaction with one another to test and evaluate the hypothesis. To do so, a combination of physical building and digital finite element analysis (FEA) was carried out to refine and improve the construction method.

2.1 Process driven technologies: understanding dynamic changes of state and statics through construction

The verification of this idea as a plausible method of designing and constructing concrete shells is based on an understanding of construction material and architectural technique. Similarly, the doctoral work of the Danish architect Manelius (2012) described an investigation methodology which embedded an extensive series of practice-based/ hands-on construction exercises. With workshop participants, she explored different ways of using fabric as concrete formwork to construct structures and to craft surfaces. To test and explore the technology potential, a taxonomy of practical investigations through experimental concrete castings was formed. In terms of methodology, the concerns and relationship between process (of concrete casting) and effect (of the resultant cast) bore strong relevance to this work.

2.2 Constructional Understanding

> *“Building at 1:1, informed by with a limited but effective body of intuition and understanding provides a broad platform from which significant areas of study – materiality, of process, of technique, can be tested simultaneously. It is only after the prototype is built that the scientific model of analysis becomes vital in refining the opportunities that full scale making has generated. The prototype tests the interaction of materials and events, not merely the constituent parts. In building a prototype, one discovers how to build, and where to focus the activity of risk, the value of team consciousness, and the consequences of theoretical decision making”*
>
> elegantly described by Chandler in
> Chandler and Pedreschi eds, 2008.

The innovation deals with technology on three levels:

- method (construction),
- aesthetic (appearance) and
- structure

The innovation suggested in this thesis deals a lot with “how to build”. An understanding of this hypothesis is gained through experiencing process by forming the gridshell, upon which fabric was attached, and onto which concrete was cast. The idea is measured by the accuracy of the formwork, ease of formwork erection and the resultant structure itself (concrete shell), their appearance as well as structural performance. Through experiencing the construction process and interactions amongst the three technologies, specific questions were formulated and methods devised and/or improved. These interrogations lie in two key concerns of formwork system controllability (gridshell and fabric) and the resultant shell (structural performance). Hence, construction becomes an important methodology through which this hypothesis is to be interrogated and understood.

Concrete casting, fabric formwork and deployable gridshells, all deal with the flux of material conditions (liquid to solid for concrete; flat mat to curved form for gridshells; and from limp to becoming hydrostatically turgid for fabric formwork). Applying concrete onto a movable fabric formwork supported by a dynamic framework (as opposed to casting into a non-moving system such as prismatic timber shuttering) demands holistic understanding of the three technologies and their interactions. The question of how to build and the interaction between materials and process/ techniques are crucial. The hybridisation of three dynamic technologies (all requiring a change of state (concrete)/ form (gridshell and fabric formwork) presents a highly complex situation requiring understanding.

The nature of all three technologies encompassed within the research is highly process driven. More general at the beginning, the research progresses in detail and sophistication.

An actively-bent deployable gridshell is assembled as a flat gridmat before being deployed into three-dimensional shapes. Similarly, fabric formwork changes from limp vacuous fabric forms hydrostatically turgid forms as it finds equilibrium between fabric, gridshell and concrete. Similarly, concrete shells are a direct consequence of the concrete curing from a liquid matter into a hard, rigid and strong structure, gaining textural expression and structural strength through form (to be discussed in Chapter 6.4). To truly understand and assess this novel way of constructing with time-dependent and process-driven techniques demands an understanding of technological interaction. In this case, experiential construction can draw questions about a new technology. This complex set of ideas and conceptual relationships are portrayed in fig. 2.2 below.

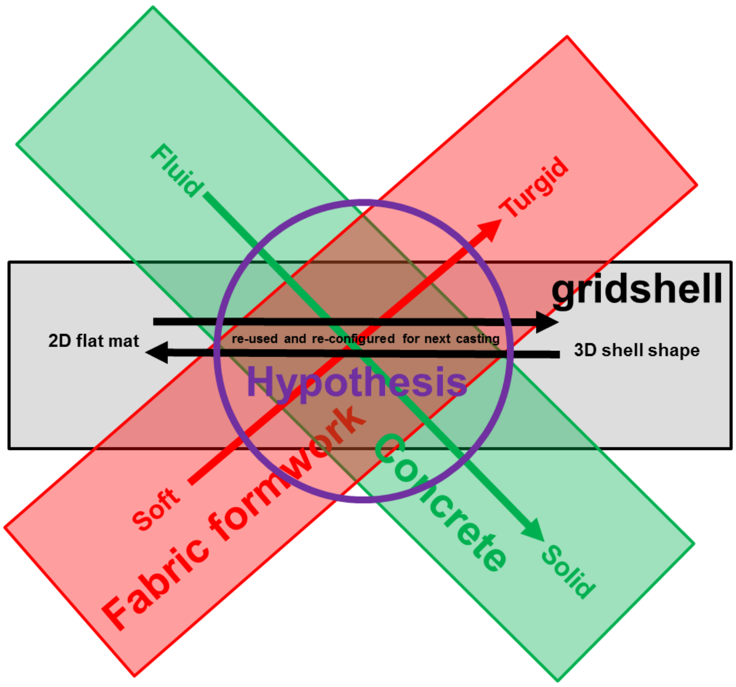


Fig. 2.2 Flux Diagram of Constituent Technologies: The relationship and interaction between constituting technologies described in the diagram above sees the changing state of concrete ("liquid stone") being supported by fabric formwork technology to form a surface stretched over a structural frame i.e. a temporarily stressed actively bent gridshell that defined the eventual shape of the concrete shell. The idea of form change is imperative for the deployable gridshell to be released and reused in another configuration where form possibilities are endless.

The type of study will be informed by both qualitative and quantitative findings, with inference from an engineering perspective (finite element modelling and mathematical analysis) understood from an architectural (history of shell technology and technical/ tectonics) viewpoint. It therefore draws influences from a wide disciplinary spectrum of architectural technology, tectonics, as well as from engineering.

Whilst experiential construction serves to understand technology and technique, the artefact (concrete shell) that results and characteristics of the construction system stands as a strong measure of the success and suitability of this technology. More than experimenting with a new construction method, a fine balance is struck between design control and allowing the method to express themselves materially especially when working with fabric formwork. Through extensive experimental construction, this understanding becomes innate, instinctive and intuitive as the designer becomes familiar with a new method. The work of Mark West exemplifies and inspires an understanding of material and technique (West, 2016) and will be discussed in Chapter 4.

2.3 The Concrete Shell: Scaled model and the unscaled artefact

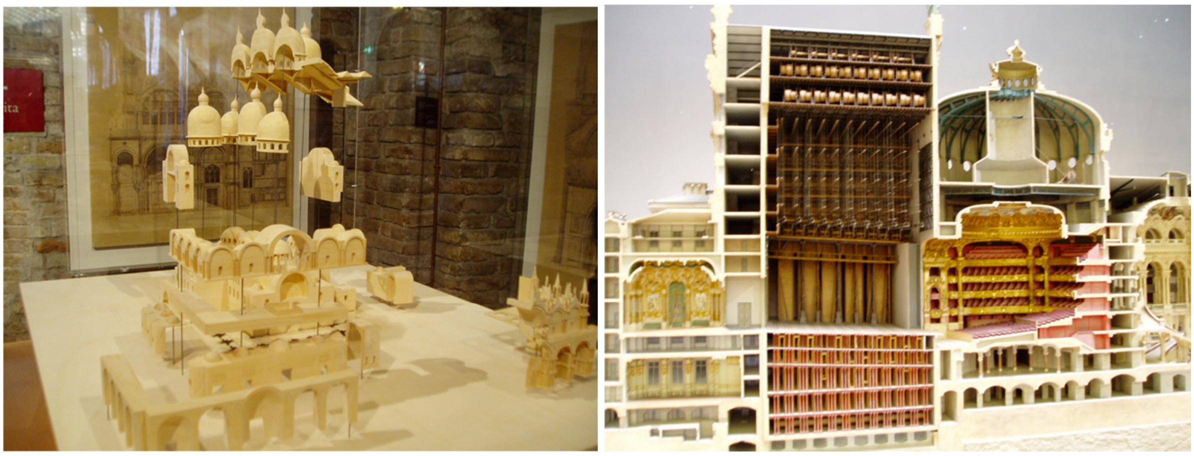


Fig. 2.3: Rather than for testing, architectural models can be representational and communicative. An exploded model of San Marco Basilica, Venice shows the hierarchical arrangements of domes and structural elements. A sectional model of the Paris Opera House portrays the spatial arrangements of auditorium and ancillary servant spaces.

Physical architectural models can be divided into three categories - preliminary, experimental and final (Gibson, Kvan and Ming, 2002). Preliminary/ sketch models are assembled for feedback whereas experimental, preliminary models exhibit bigger control over dimensions whilst final models aimed for verisimilitude (Gibson, et al, 2002). Especially in architecture, the experimental function of the physical scaled model as a medium of depicting form and space during design process to convey design intent is commonly used (Eissen, 1990). On the other hand, physical models are used to communicate architectural results. Final presentation models of museums when they are completed with a real likeness to the actual building do exactly that, and are often appreciated in their own right (Hubert, 1981).

Modelling Construction Sequence

More relevant to this study, Gibson et al pointed out that models can be used to test constructibility. Construction process and design can be simulated through the stages of making a model or erection process. As well, complex geometries could be examined through constructing physical models. This is especially true for shells and other complex geometrical forms that impact on space planning and building services provisions (Janke, 1968). In this enquiry, this function/method is heavily relied upon.

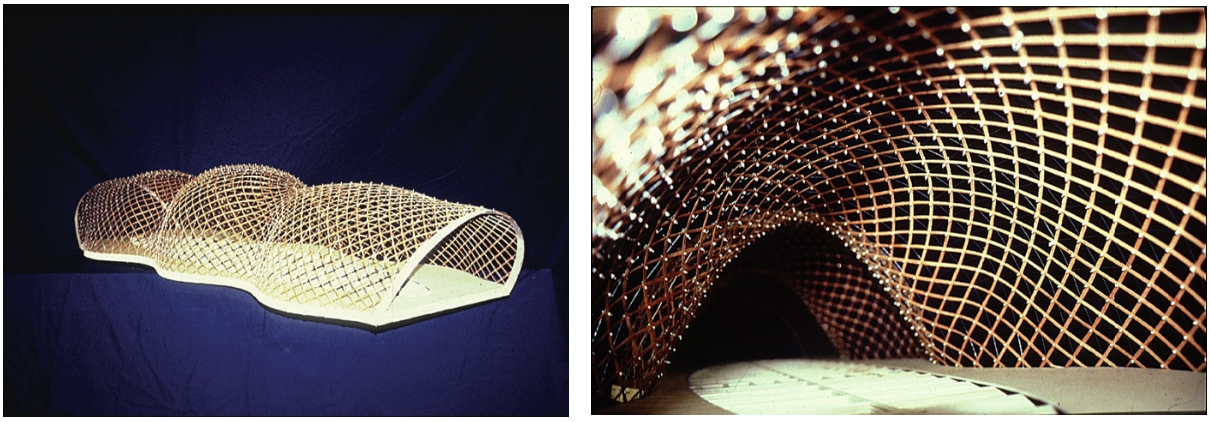


Figure 2.4: The scaled model of the Weald and Downland gridshell demonstrated the spaces within the gridshell enclosure.

This function is exploited in the 2002 Jerwood gridshell at Weald and Downland Open Air Museum, UK. The physical model was instrumental to the success and understanding of construction process innovation and solving problems that ensued. The architects, Studio Cullinan recognised the important role of physical models in the design of the structure and communicating with the design team. Unlike static hanging chain models used previously by Frei Otto, a physical scaled model of 1:30 was constructed from wood with the form found digitally by Chris Williams at Bath University. To further investigate the idea of deployability, yet another model at the scale of 1:43 was made out from wire mesh. Not only representing the space within the structure itself (Chilton and Tang, 2017), the physical models was instrumental in helping the design team to understand and construct double-curved structures and appreciate the dynamic shell- forming process and develop form deformation i.e. the construction sequence, an essential method for the contractor to test out the propping procedures too. According to John Romer, one of the architects responsible for the celebrated timber gridshell –

> *"…with the physical model, you will be able to come up with what you think is right and put it into the machine i.e. the computer. The computer can then give you the answers. The model, gives you the question."*
>
> Romer, 2009, in Chilton and Tang 2017.

In the fields of structural engineering, physical models have been used differently from architectural models as tools of representation. Models were constructed to test building behaviour in specific conditions. This approach was born out of the necessity at a time when computer analysis was at its infancy. Simulating various loading conditions, the physical model allowed building responses to be checked and quantified. Specifically, scaled models were used reiteratively, and to great effect, by the engineer Eduardo Torroja to instil construction confidence. For the Fronton Recoletos sports hall in Madrid, he used a simple sketch card model with end walls made of wood to confirm the overall thickness of the curved form to ascertain the need to provide firm support to the longitudinal edges of the curved shells. Once confirmed, to further understand deflections, a scaled 1:25 model was built and tested against calculated deflections that conformed to scaled simulations of dead and live load cases. This reiteration between scaled models and manual calculations inspired confidence to construct the design eventually (Addis, 2008). The pioneering methodology of testing complex geometrical structures with relatively simple mathematical calculations inspired structural understanding and building confidence in the technology of concrete shells.

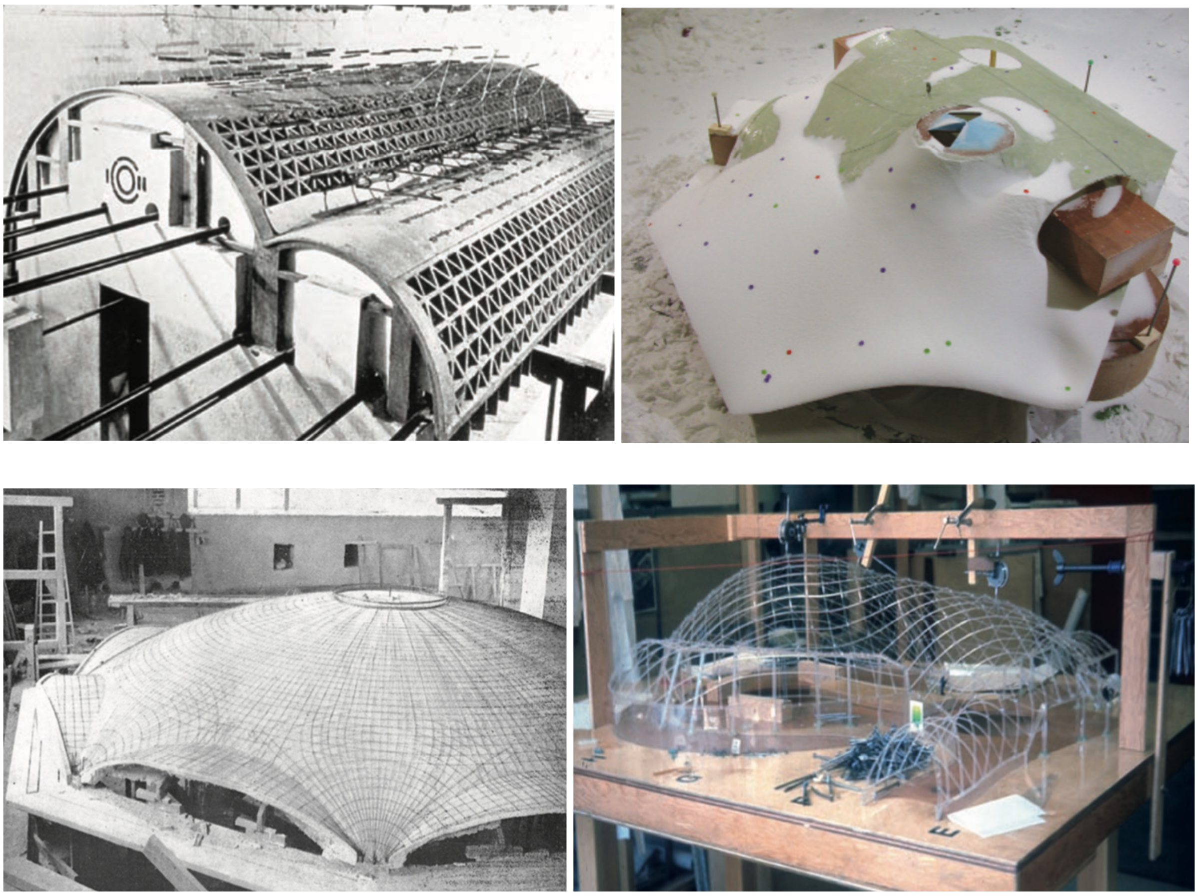


Figure 2.5: Top left: A scaled model of the Fronton Recoletos was developed in the great traditions of modelmaking for structural testing to inspire confidence in concrete shell construction prior to computerised structural analysis (from Addis 2013). Top right: 1:30 scale physical model for snow drift/ loading testing carried out by the Centre Scientifique et Technique du Bâtiment (CSTB) in Nantes, France to test for snow loading for Pompidou Metz, engineered by ARUP 200 (from Lewis, 2011 copyright to CSTB) bottom left: Roof of Algiceras Market Hall at a scale of 1:10 constructed from micro concrete, 1933 by E. Torroja. Bottom right: 1:60 Mannheim Multihalle gridshell tested in elastic range scale 1:60 (copyright Ian Liddell, from Addis 2013)

2.4 Collaboration

2.4.1: Learning by building (Carpenter, W, 1996): Building with Architecture and Technology Students

In initial workshops, student participation and interactions explored and facilitated a collective learning of designing and constructing gridshell structures. In architectural education, experiential construction simulated construction process and on-site problem-solving. Architecture praxis is collaborative and required the coordination and working together of expertise within and outside architectural disciplines. This need to collaborate and work together is especially crucial in dealing with the design and construction of structures heavily influenced by shape, construction method and/ or sequencing such as that proposed in this research program.

2.4.2 Structural Analysis with Engineering Students and Structural Engineers

A running theme of this research deals with collaboration with structural engineers (finite element expertise, analysis and verification). Although the research is conducted with a strong architectural perspective of technology in mind, a mathematical and digital verification reiterative to the design process is indispensable to supplement and verify this feasibility objectively. The limited viability to construct a complete building from such a system is limiting due to practical reasons. Physical structures i.e. test shells were systematically tested, the behaviour recorded and analysed with the help of structural engineering researchers by testing concrete shells at elastic range as well as to collapse. It is also important to understand the resultant shells qualitatively. Hence, digitally simulated loading conditions on finite element software programmes e.g. Oasys are used to understand structural behaviour with structural engineers.

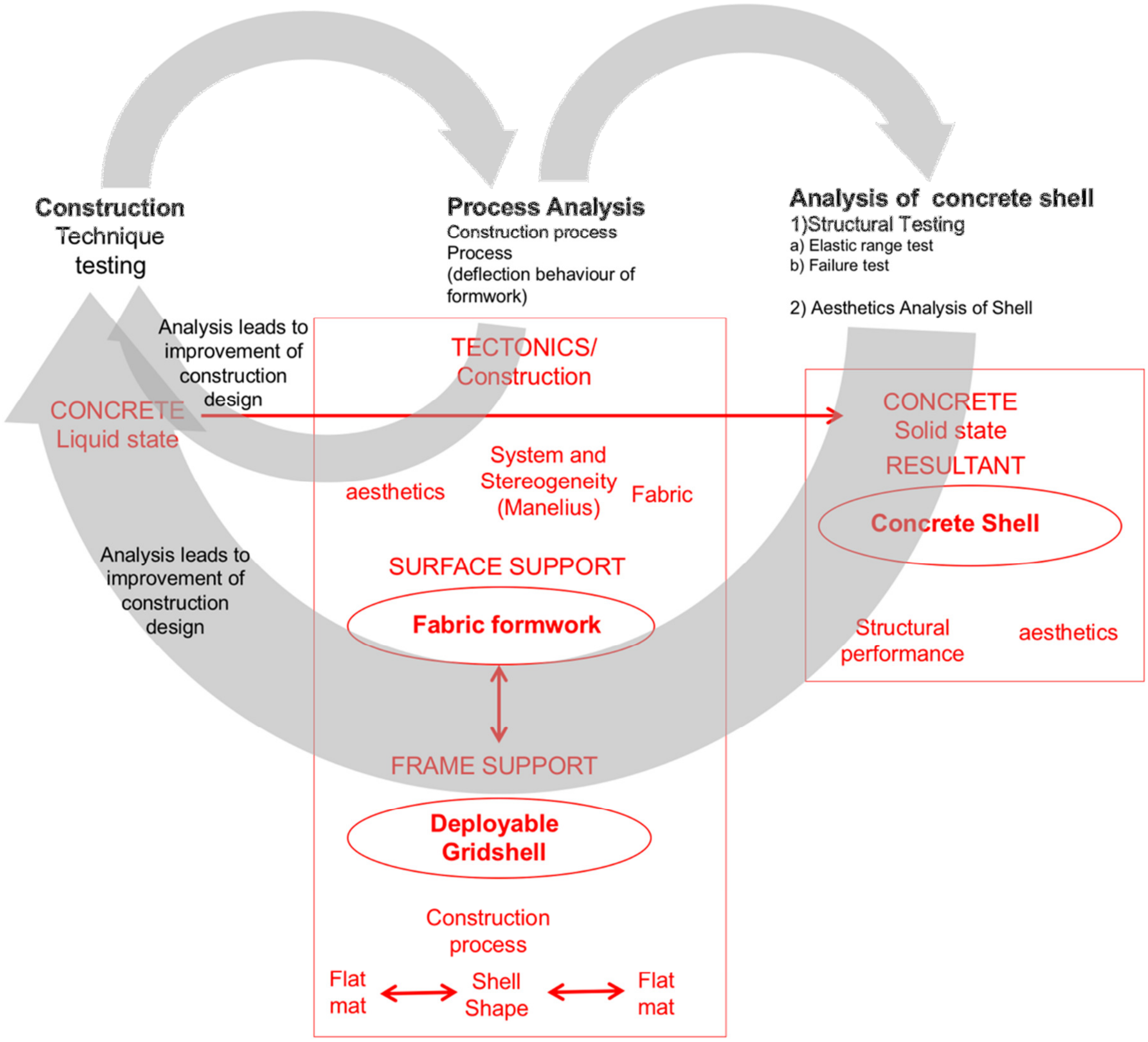


Fig. 2.6: The process of analysis is reiterative. The diagram shows the initial construction of test shells, which undergoes an analysis of process (construction) followed by the analysis of the resultant concrete shell. This process is carried out for all test shells.

2.5 Understanding the effects of construction: Process, Process, Process

A thematic thread of this research weaves the applied technologies of deployable gridshells, fabric formwork and concrete shells together in their process-intensive nature and the understanding of how these systems interact. Not only are concrete shells concerned with the end result, as with fabric formed concrete , identified by Pedreschi in 2008 (p22), processes used to form the object could either be declared or denied. In this case, the use of actively-bent gridshells as formwork declares their processes thrice. The final form has total dependence on each other and is intrinsically conditioned by the process of creating the deployable gridshell, the fabric formwork and the eventual concrete shell. Here, processes are fundamental to understanding technique. This understanding of method and material can only be fully understood, even at a smaller scale, by experimental and experiential construction to test, improve and innovate through designing and making e.g. prototyping. This methodology of shell understanding is common to key designers of concrete shells (e.g. Felix Candela and Luigi Nervi) who through building, learnt to improve their designs.

The dynamic change of states of the gridshell frame, fabric surface support and resultant concrete shells are concerns to address too – concrete begins life from a liquid state turning solid; deployable gridshells lie as a flat extendable mat to deform three dimensionally; whilst fabric formwork begins by being limp to become hydrostatically turgid forms when filled with concrete. In this regard, the purpose of the model and construction exercises extrapolate the three main themes of construction, aesthetics and structure.

To develop a physical construction is an indispensable part of the research to experience technology and to develop technique. The research focus directs the methodology reiteratively, liken to commercial R and D (research and development) activity where the research is progressively improved and perfected. To understand a new technology/ method from an architectural standpoint involves the appreciation of the new method from three levels:

1. Construction Process through simulation of actual construction
2. The tectonic aesthetic
3. Structural performance of process and result through load/ deflection testing with digital analysis

2.6 ***Flash*** Research (Benjamin, D. 2012)

> *"……habit has largely taken command of imagination. Conventional industrial methods of construction and design in concrete take place in a highly evolved traditional system where prismatic forms are a foregone conclusion."*

West , 2016 on the conventionality in construction.

In his book, West (2016) laments the conventionality of constructional thinking, questioning the value of prismatic molds in concrete casting. Conventionality is perceived as barrier to innovation. This questioning exemplifies the free-thinking spirit, and problem-solving by first principles rather than through conventional problem solving i.e. solving problems in the normal way. This approach was explored by Benjamin through the mode of *Flash* research.

In 2012, Benjamin, D. published a form of research he called *Flash* research. *Flash* Research “involved targeted, intense explorations of architectural ideas within self-imposed limits of time (3 months) and a budget ($1000). This methodology tested design possibilities through full-scale, functioning prototypes." Limiting the budget and time may be arbitrary to some, but the intenion of doing this helps to "contain" the mode of exploration.

Flash research was not only the research format adopted in this research; the spirit of enquiry and problem solving is relevant and aspirational. Benjamin attributed the series of construction experiments as being inspired by informal experimental activities that took place in a garage in Los Altos, California in the 1970s and 80s. This was in fact the garage where Steve Jobs and his friend Steve Wozniak began their ventures into computer technology which led to Apple Computers! The garage was a space for combining concepts with physical materials, through experimentation and prototyping. This was where they Apple founders challenged conventional thinking in a maverick and un-institutional manner to innovate and invent.

In fact, *“The garage was a place to say f*** you to the way things are usually done.”* Benjamin, 2012, p143.

Benjamin's methodology of flash research benefits this research in a number of ways. Principally, the research interest is intellectually protected from status quo and conventionality. In an un-institutional setting, this form of research conducted at the beginning is allowed to develop freely and creatively, in a fluid way. It is in these situations where findings and inventions would most likely lead to unexpected and coincidental innovation.

This research methodology is relevant to this study as ideas are tested through a series of experimental constructions to establish and define research questions. Intentionally free, unrestricted and untainted by conventionality (in neither material nor method), but restricted by time and budgetary constraints, the research explored general ideas and material processes. Influenced by this nature of *Flash* Research, the activities took the form of student construction workshops on gridshell construction (discussed in Chapter 5.6), which through repeated construction cycles, attempted to perfect the method, eventually leading to the hypothesis.

In the same free-spirited manner, the goal of this research is not to solely refine a commercial method of casting concrete shells, but to record new experimental evidences and identify research possibilities. *Flash* research allows the exploration of the interstices, synergies and intersections between existing technologies which have traditionally existed independently as standalone solutions.

Without consciously adhering to this research mode, variations of *Flash* Research was carried out in at Edinburgh University in projects led by Prof Pedreschi and by Prof Alan Chandler (University of East London), as well as at many other institutions world-wide where concrete and fabric formed technologies were explored in a defined time limit (1 or 2 semesters), very often also with a limited budget. Some examples are presented in Chapter 4.11.

The research methodology here applied elements of *Flash* Research through exploring ideas within a limited time frame and involved making prototypes to test ideas. This explorative methodology relates well to elements of this investigation especially in checking for behavioural changes which was discussed earlier. Firstly, time constraint effectively focuses on innovation intensity. Secondly, prototype construction, even at a smaller scale, facilitates an understanding of aesthetics and process.

Flash Research in the form of life-scale explorative construction had led to the main research question, to drive this research enquiry. It is through this *Flash* Research mode that this missing gap in knowledge was discovered. Subsequently, objectives were assessed through a systematic program of construction/ prototypes designed to produce qualitative (observations of shape change, casting anomalies) and quantitative outcomes (numerical outputs from finite element analyses.

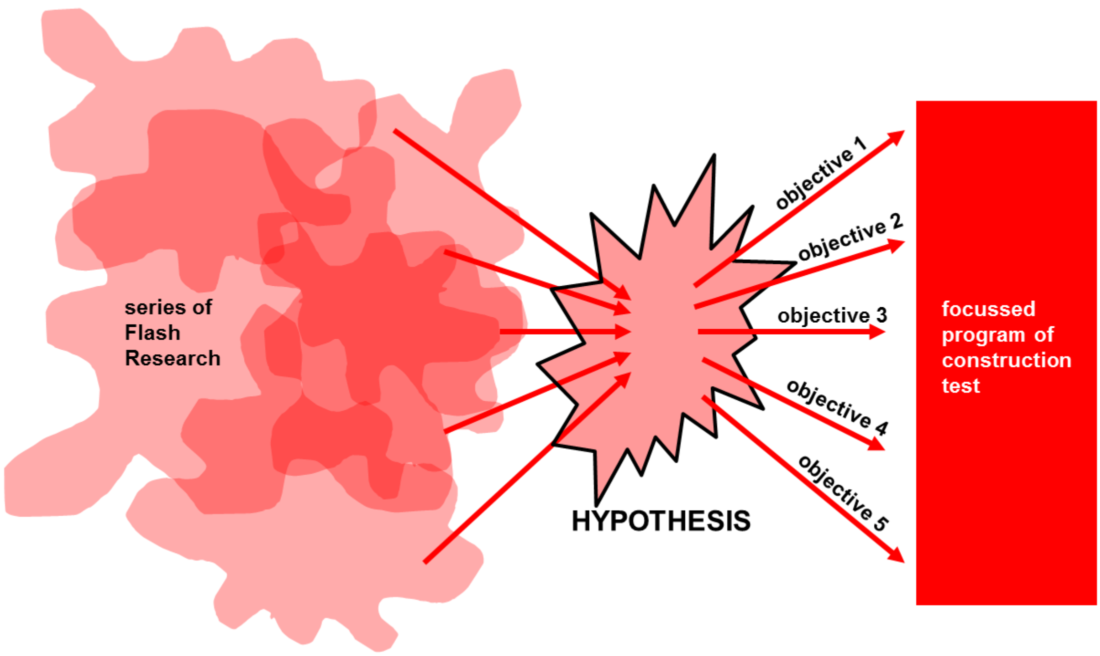


Fig. 2.7: A series of *Flash* Research exercises consolidated into the formation of the hypothesis. Specific objectives were distilled from the hypothesis through literature review and through physical constructions. Each objective focus is tested through a series of construction tests to assess the method and discussed.

2.7 Research Questions

The hypothesis lies on using deployable and actively-bent gridshells to construct concrete shells forms the basis of this research. To investigate this, a series of constructions is formulated to address a number of specific issues.

2.7.1 Questions on Formwork:

- Can a deployable gridshell be used as formwork for casting concrete shells?
- Is this formwork re-usable?
- Is this formwork deployable?
- How deployable is the formwork?
- What is the behaviour of the gridshell before, during and after casting?
- How easy is it to remove the gridshell after concrete is cured and hardened?

2.7.2 Questions of Shell Casting Process:

- Observations during the casting process: what was the ease of applying concrete on the system and how does this affect the shape of the resultant concrete shell?
- What is the behaviour of gridshell before, during and after the casting process?

2.7.3 Questions on the Resultant concrete shell:

- The geometry and shape of the resultant concrete shell
- How strong is this concrete shell?
- How stiff is the resultant concrete shell?

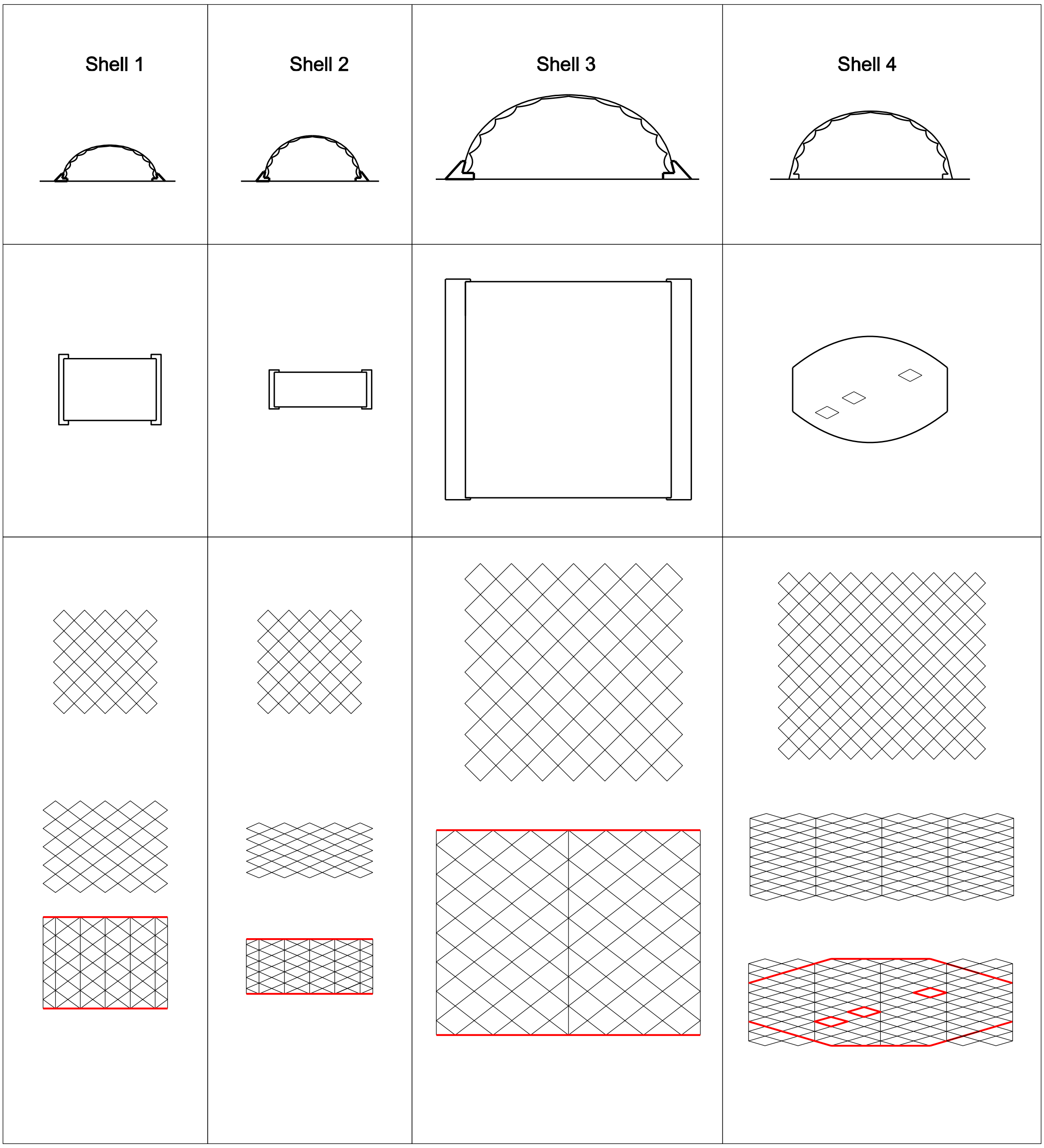


Fig. 2.8 Chart of Experimental builds using deployable and actively-bent gridshells as formwork to cast concrete shells.

Fig 2.8 above describes a series of Test Shells designed and constructed to understand specific aspect of the design idea. Each experiment is elaborated in the following section:

2.8 Key Elements of Research

To address issues raised by these questions, a series of construction exercises were formulated and carried out to test this novel method. Inferences, evaluation and deductions were made from each experimental build. The following section presents key points of the research design. The following section refers to fig. 2.8 to give an overview of the test designs.

2.8.1 Gridshell Material

The detrimental reaction to wet weather conditions, as experienced by the failure of the shell constructed outdoors at Sheffield Hallam University in 2011 (Chapter 5.6.3), water and weatherproof glass reinforced plastics and metal gridshells are considered and used. Additionally, materials were selected for their cost and workability.

2.8.2 Concrete Mix

The concrete mix determines the strength of the resultant concrete shell. Additives to retard or accelerate concrete curing process as well as fibres reinforcement can be varied to adjust the quality of the concrete.

2.8.3 Reinforcements in concrete

Traditionally, tension cables, reinforcements bars and metal meshes can be incorporated into concrete shells and thin shell structures to enhance structural performance of such structures. Free-form shells have proved that metal mesh covered with concrete can be achieved, sometimes artistically, without strong structural reasoning. However, for this set of concrete shell construction, the use of specially designed reinforcement bars is excluded to focus on structurally un-adulterated structures.

2.8.4 Verification of Construction Method

Test Shell 1 and Test Shell 2: The first set of construction was carried out to verify this hypothesis on fundamental level. This construction consists of two simple vaulted shells with simple geometries using the same gridshell employed to support a fabric layer and concrete applied on top. This aimed to establish the re-usability and re-configurability – two prime aspects of this idea. Gridshell formwork movement behaviour during the construction process was assessed, monitored and analysed.

2.8.5 Scale, complex geometry and an alternative gridshell material

Test Shell 3: The third experimental build was designed to test the construction at a larger scale in an attempt to produce a different geometry. The material of choice (metal strips) was experimented and chosen to test for their viability and implications as a gridshell formwork material.

2.8.6 Change in geometry, Openings and Free-edges

Test Shell 4: The final construction was built to express double-curvatures, openings and free edges to demonstrate what these gridshells are capable of producing.

2.8.7 Structural Analysis and Evaluation of resultant concrete shell strength

The resultant concrete shells undergo a series of deflection and failure testing and finite-element analysis directed by MEng students and engineering collaborators. The relationship between deployability, improvisation, construction process and behaviour are comprehensively noted.

2.8.8 Understanding construction processes

The interactions between the three technologies and tectonic expression by applying system on a current example of a deployable gridshell. Limited by resource and practical issues, building the concrete shell at 1:1 scale could not be practically performed. Hence, this idea is tested out in a design exercise based on the simulation of a concrete shell construction cast onto the existing Weald and Downland gridshell as formwork. Imagined as constructed of two cross layers of glass fibre reinforced tubes, an understanding of construction method at reduced scale of 1:20 partially was made from glass fibre reinforced polymer tubes. To support a thin layer of concrete (or plaster), plaster impregnated fabric bandages were stretched similarly to the way earlier prototypes were constructed. To further understand the construction process, a 1:20 scaled model of the Downland Gridshell was built to simulate the possible construction stages of using the gridshell as being covered with concrete and then decentred. The spatial expression that resulted forms an impression of how the concrete shell which results may look and feel like.

To establish a structural understanding of this method when applied, finite element model of the Weald and Downland gridshell will be applied to understand the system computationally. To address this, the finite element model digitally will replicate the construction of a concrete shell using an actively-bent gridshell. The well-established and well-documented gridshell is specifically chosen to be used as a form-found and constructed gridshell as the project stands as an exemplar of a well-defined shell form. It is also the culmination of improvements of construction technologies and form-finding methods used in the design since the 1976 Mannheim Multihalle as well as further developments discussed in Chapter 5 (Chilton and Tang, 2017).

Simulation methods (as defined by Groat and Wang, 2013 as a mode of architectural research) were employed to experience challenges/ limitations brought about by cost and practicality issues at full scale e.g. an actual concrete shell structure standing 9.5m tall. To address this, finite element analysis is used to verify the hypothesis to understand loading behaviour of the system (gridshell) and the structural behaviour of the resultant artefact (concrete shell).

Detail, Chapel Lomas de Cuernavaca, Mexico by Felix Candela (1959), 2017 (Gabriel Tang)

PART 2 THE CONFLUENCE OF TECHNOLOGY

Chapter 3 CONCRETE SHELLS

Chapter 3 Concrete Shells:

Concrete

> *'Concrete is the material of change, of metamorphosis. Like a chameleon it appears in different disguises and in different contexts. The assessments of this substance have changed over the years. In the early modern period, it was considered to be a miracle material, which would solve all the problems of the building industry. Later it was seen as representing the inhuman scale of large building projects and sharply criticized. In many ways concrete is a universal material. It can take any form and shape, and it is made up of raw materials, which are so commonly found that they can be extracted and produced virtually anywhere. Still, concrete represents particular values that are hard to define but, at the same time, seem to be associated with modernity in architecture by many.' …*
>
> Wedebrunn, 1997.

> *"Concrete has next to no opinion about its shape; a wet, heavy, gloppy material, it will take any shape you give it, so long as you can hold it still for a few hours"*
>
> Schjeldahl, 1992.

3.1 Introduction

Concrete shells are beautiful structures. Designed correctly, they efficiently span large distances with minimal material use. They are the embodiment of materiality and construction process, involving the collaborative working between architects, engineers and builders.

The mid-20th century heyday of concrete shells saw a requirement for large-spanning spaces in the form of religious, recreation or industrial purposes (warehouses, grain silos, concrete cooling towers). As they could be built quickly and efficiently, concrete shells readily met this need. Increased industrial processes also brought about the need for grain storage silos, goods warehouses and transportation interchanges. The 1950s was an exciting period of post war optimism as the characteristic fluid/ curved shapes of concrete shells came to signify modernity, representing the aspirations of the period.

Exposed concrete interiors possess a material sensibility that some perceive as contemporary and modern. It is after all, a material of future possibilities (Calder, 2015). Increasingly accepted as an interior finish, bolstered by advancing technologies of better mixes and additives (retardants or accelerators) designers could tailor a material specific to its application. This was seen in how Romans mixed concrete of different weight to be used at different sections of the Pantheon dome- lighter volcanic pozzalan stones were used in the concrete mix at higher sections of the dome while heavier granite stones were used (Addis, 2008). As well and aesthetically, concrete shells readily expressed the construction process (i.e. tectonics) through the imprints of their formwork.

In countries with low labour cost, concrete shell construction presents an economical method of building. In developing economies such as India, where labour is cheap and readily available, concrete shells are still being built (Sundarum, 2012). Low labour cost was one of the key reasons that led to their popularly in post-war Italy (Nervi, 1960).

After decades of diminished presence, the resurgence in concrete shell is witnessed in recent commissions and realisation of concrete shell structures is seen from the works of SANAA (Teshima Art Museum in 2011) and Grin Grin Park by Toyo Ito in 2005. This is an intriguing phenomenon. It is important to examine their re-appearance through an understanding of the factors that led to the rise in popularity and their re-acceptance. Conversely, their fall and rejection also deserve interrogation. Tackling the reasons that led to their demise may offer the solution to solve the problems of formwork and design/ construction methods.

Fig 3.1 Kakamigahara Cemetery, Japan concrete roof 2006.
(http://www.toyo-ito.co.jp/WWW/Project_Descript/2005-/2005-p_07/2-800.jpg)

To understand the evolution of concrete shells, various aspects of these shells have to be understood.

3.2 Proper or Improper shells

Concrete shells are a family of surface structures (Angerer, 1965). Efficient shells carry load primarily through membrane forces (Isler, 1994). The absence of large bending forces keeps stresses low, in turn reducing material demand i.e. keeping shells thin. In other words, the structural performance of a shell is dictated by its form (Hawkins, W. J., et al, 2016).

Load transfer in shells is dependent on their geometrical shapes. Therefore, shells must be designed correctly to allow an even self-weight distribution on the surface of the shell (through membrane stress). An incorrect geometry can result in high concentrations of stresses in certain parts of the structure which may cause it to crack or completely collapse. To design shells which allow full use of their characteristic is both an art and a science requiring spatial and structural understanding. A "correct" structural shape/form allows the perfect stress condition (wholly compression) to occur. Engineers and architects explore the morphological aspect of shell structures in a process called *form-finding*.

Shells derive strength from their shapes. Two families of shells have been in existence but were formally described by the shell builder/ designer Felix Candela: proper shells (those that avoid bending stresses and doubly-curved) and improper shells which carry loads through some bending action (Garlock and Billington, 2008). Proper shells carry load through membrane stresses and possess either pure compression or pure tensile stresses (i.e. without bending moments) whilst improper shells are characterised by bending moments.

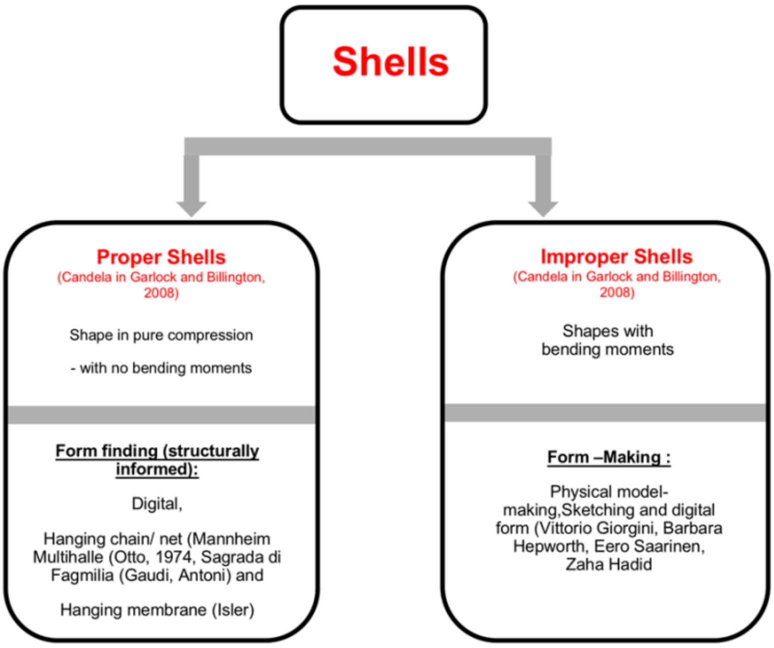


Fig 3.2 The classification of Shells (Candela in Garlock and Billington, 2008)

Fig. 3.2 represents one way of classifying shells. Shells are divided into two categories: proper (pure) shells and improper shells. The definition of shells is partly informed by their structural function. A layperson (including architects and engineers) understanding as concrete shells is due to their easily recognisable shapes. Structural morphology is significant in shells. Although shells are widely recognised by their double curvatures, "structurally-correct" shells, in fact, maximise their geometry potential by increasing structural efficiency to minimise material use (and therefore reduce material cost). These geometries can be generated computationally (dynamic relaxation) or more traditionally through hanging models (elaborated in Chapter 3.3.2.1 and experimented in chapter 6.3.1). However, being able to produce efficient shaping does not ensure that this method of construction is most cost efficient. This is due to the difficulties experienced in constructing these double curved surfaces which will be discussed further in Chapter 3.9.

3.2.1 Improper Shells

Although no formal records of structural analysis are available, Herwig (2016) published photographs of a collection of expressive concrete bus stops built in Soviet USSR which are suggested as improper concrete shells. Improper concrete shells can be (but not always) free-form and expressive made possible by the introduction of re-bar meshes and/or thicker concrete walls that rectify bending moments within the structure itself.

Fig 3.3 Soviet bus stops as “improper shells” (Herwig, 2016).

Whilst proper shells are governed by geometrical rules and structural rationale, improper shells are explored and derived through a process of form-making (as opposed to form-finding in proper shells) in a way which is freer and less constrained by structural concerns. Just like the bus-stops in USSR, double curvature concrete shells can be cast into expressive shapes with re-bar meshes and thickened concrete walls allowing designers to express their artistic intentions, rather than structural reasoning. Some examples of improper shells are discussed below.

3.2.1.1 Winged Figure 1

Barbara Hepworth

In a similar way, the idea of improper shells can be loosely applied to the sculpting process of Barbara Hepworth (1903-1975). Hepworth is a British sculptor most well-known by her works characterized by doubly-curved surface forms, some appearing shell-like, and with openings. The form-making process for Winged Figure 1 (1963) commissioned by and designed/ constructed for John Lewis store on Oxford Street, London in 1963 is relatable to this discussion. Although eventually cast in bronze, the form-making and prototyping was in fact designed (form-made) in timber sections. With this “rough draft in timber”, scale and form implications of the eventual sculpture was immediate (Bowness, 2011). The sculpture exemplified creativity, free of the distracting need for structural efficiency.

What was interesting was the process by which these forms were conceptualized. Whilst to some, the mock up (fig. 3.4) bore reference to the framework of a boat in construction, the same prototype mock-up with armatures and framework is reminiscent of a timber gridshell.

For this sculpture, right-angled lengths of aluminium formed a skeleton that supported and strengthened the sculpture whilst sheet aluminium clad the entire structure textured with *isophon*. The aluminium sculpture was then delivered to a foundry for aluminium casting in full (i.e. not hollow) in 4 sections which was then welded together. The outcome was an unintentionally improper shell.

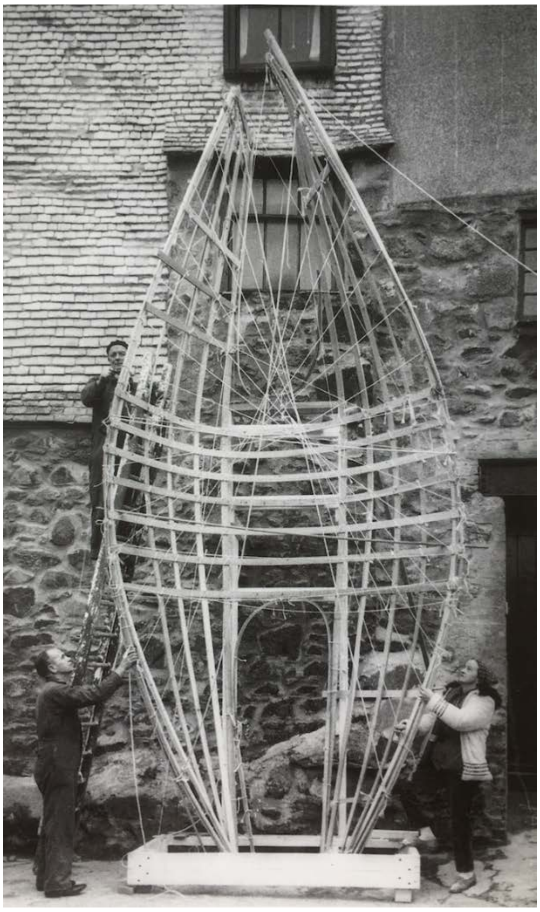
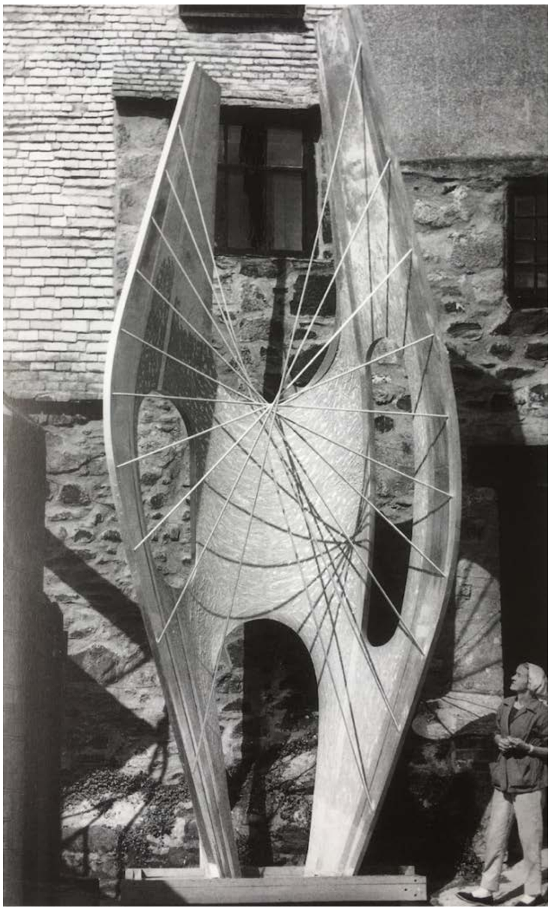



Fig 3.4 Winged Figure 1 for John Lewis, 1963 (Hepworth Archives)
Left: "A rough draft in timber" where Hepworth used timber and rope to describe and understand the final sculpture. It was used for "the preliminary delineation of form in space"
Right: the aluminium version of the sculpture ready to be brought to the foundry for full casting. (Hepworth Archives)

3.2.1.2 Liberty Centre, Upstate New York, 1976 (unfinished)

Vittorio Giorgini

Vittorio Giorgini is a Florentine architect who held the post of Professor at Pratt Institute in New York. His work and teaching dealt with ecological ideas of architecture and often produced intriguing shell forms. Clearly these "shells" were neither structurally derived nor were they "geometrically correct". This free-form use of concrete was supported by wire-mesh that created interesting shapes to be concreted for creating organic forms. To achieve this, Giorgini used an iso-elastic membrane made of wire-netting. The Liberty Centre wire-mesh tantalisingly suggested what it could be when/ if completed. The photos below show the sacrificial wire-mesh formwork constructed by Giorgini and his students at upstate New York. Sadly, due to the lack of funding, the project was left unfinished and unconcreted (Giorgini, 1996). Again, this structure was not driven by structural ambition, but formed fine examples of elusive and yet to-be-finished improper shells.

Fig 3.5 Liberty Centre at Upstate New York created and built by Vittorio Giorgini in 1976 (copyright Vittorio Giorgini Archives).

3.2.1.3 Kresge Auditorium, MIT Eero Saarinen 1955

Eero Saarinen's Kresge Auditorium at MIT (1955) is another example of an "improper shell" (Candela in Faber, 1963). The doubly-curved roof was designed and intended to be a self-supporting shell but because of geometry, would not be structurally efficient nor effective. This "improper shell" is a point supported segment of a sphere where side measured 48m. Eero Saarinen chose this shape solely for its geometry (Chilton, 2000) and not for its structural efficiency. As such, the structure suffered problems. To correct this structure, 0.93m deep columns had to be built along the glazing wall to support the edge beam!

Quite different from the Liberty Centre and Hepworth's works, this project was conceptualized as a structurally functioning shell but failed to work the way it was intended.

Fig 3.6 Kresge Auditorium in MIT: external view (top) (https://dome.mit.edu/handle/1721.3/34960) and internal view (bottom) (http://larryspeck.com/2014/03/07/kresge-auditorium/) by Eero Saarinen was not a pure/ proper shell. Initially designed as an efficient shell, however due to the imposed geometry of roof, being conceptualised as an eighth of a sphere, it could not perform optimal shell action. Corrective columns hidden within the mullions were incorporated to support the edges of the shells.

The project was deemed controversial. In 1964, the artist George Maciunas criticised the design strategy as a “non-functioning 3- support ‘efficient’-looking dome and supported with inefficient but well-concealed columns.” In the following decades, this criticism grew, bolstered by scholars such as David Billington (1983) and Robert Mark (1990), who repeatedly used the building as the canonical example of the dangers of employing willful “geometric-” instead of “structural-” shapes in shell design (Plunkett and Meuller, 2015). The construction was plagued with inconsistencies to a structural understanding, opening up questions about the relationship between technology and architectural design. This led M Richards to ask an interesting question about the position of technology in architecture practice: “…….whether technology (structure) is to be servant or master, and then of what kind of service.” (Boothby, T. ; Parfitt, M. Kevin; Roise, Charlene K, 2006).

Fig 3.7 The Kresge Auditorium is completely different from the free edges of Felix Candela's 1958 Los Mantiales shell. A a non-load bearing glazing system declared itself clearly as a non-structural element that separated it between the inside and outside. (bottom).

3.2.1.4 Kimbell Museum, Louis Kahn, 1972

Another case of architects designing "improper shells" can be seen in the rooves of the Kimbell Museum, Fort Worth, USA constructed in 1972 where Louis Kahn mis-conceptualized coffered ceiling roofs as shells rather than as beams.

Fig 3.8 (top): external photo showing the recurring external arrangement of the roof. http://www.eubankroofing.com/images/projects/kimbell_art_museum.jpg (bottom) The internal spaces defined by the roof © Amit Khanna - Design Principal, AKDA

According to Meyer (1979), the choice of the cycloid (the curved profile of the vault) was inspired by Kahn's reading of Fred Angere’s book Surface Structures (1961). The cycloid described the outline of the “vault (was) derived from the path of a fixed point on a rotating circle moving from one side to the other. The engineer, August Komendant, one of the leading world experts on shell construction, was then asked to solve this structural problem by making structural changes to allow Kahn’s “deceptions” to be made buildable. To make these 100 feet long, 23 feet wide vaults work, they were pre-cast and post-tensioned with cables to alleviate high bending stress conditions within the "vaults" themselves. (Komendant 1975, in Dormer, 1993).

“The arch shape confused him so he considered a shell primarily an arch and not a beam, which it actually is. Due to this, the shell roof design was structurally completely wrong.” (Komendant 1975, in Dormer, 1993).

The Kimbell Museum is not alone in dealing with this fine line of definition between "proper shells" and other structural systems. Contemporary architecture sees many examples of the mis-application of shell-like structures by architects and the general public.

3.2.1.5 ROLEX Centre, SANAA Architects 2010

The Rolex Walking Centre appears to be a concrete shell on first look. It actually consists of two shallow shells (with large bending moments) connected by a pre-stressed plate (fig 3.9 below) constructed with an extensive use of reinforcement bars. The low curvature and the asymmetric arch geometry presented large bending stresses requiring a high percentage of steel reinforcement of up to 470 kg/m3 to correct this. The reinforcement was not only necessary for the transfer of traction in zones with high bending moments, it also reduced the long term deflections due to creeping and shrinkage (Weilandt, A., Grohmann, M., Bollinger, K., & Wagner, M. (2009).

Fig 3.9 ROLEX Learning Centre, EPFL. (copyright Weiland et al, 2009)

The above built examples illustrated different cases of improper shells. Improper shells can be born from the intended need to achieve structural purity (of pure compression) but failed. Alternatively, it can be a coincidental arrival to thin double-curved forms which are often recognised (by the lay person) as shell structures. The examples also showed that improper shells can be correctively engineered when the shape was "structurally incorrect", resulting in excessive undesirable bending stresses.

3.2.2 Proper Shells:

Unlike improper shells, proper shells transfer load efficiently by the nature of their shapes (form). These structures possess little stresses on their thin surfaces as all loads are efficiently transferred. Proper shells are not designed arbitrarily or co-incidentally; rather, their design is motivated by the quest of shapes with most load transfer efficiency. As curved surface structures (Angerer, 1965), shells are intrinsically linked to their shape. The search of this efficient shape/ geometry is conducted through a process known as form-finding.

3.2.2.1 Formfinding

Formfinding of shells is conducted in two main ways- computationally or by the use of physical models, or as a reiterative process combining both methods. How the designer finds the desired shell shape is an interesting question.

The word form-finding is an intriguing term. It suggests an “answer” or a perfect (structural) condition. Architects and engineers search / explore iterations of shell shapes physically (model-making) or computationally (e.g. dynamic relaxation). The term "form-found shapes" exudes a notion of finiteness, a solution to a structural/ form problem i.e. optimization of forces, efficiency of load transfer and an economy of shell material (e.g. concrete).

Over the course of history, Frei Otto, Heinz Isler and Antoni Gaudi used hanging chains to find pure compression shapes without bending moments. This process has main considerations on force transfer and shape efficiency, (as with all proper shell form-finding), but do not usually take into account construction method or forming/ casting at the early design stage. In the 70s, hanging chains and nets were frequently used at the Institute of Lightweight Structures ILEK (University of Stuttgart, Germany) for gridshell form-finding (Chilton and Tang, 2017). The Catalan architect Antoni Gaudi also employed sophisticated hanging chain models to design the Sagrada di Fagmilia church in Barcelona. It is assumed that a chain of gridded mat with particular restrained points would create a shape that acts in full tension in accordance with Hooke’s Law of Inversion named after the scientist Robert Hooke (1635-1703) (Adriaenssens, Block, Veenendaal and Williams, 2014, Chilton and Tang, 2017). When inverted, these forms act in pure compression without bending action. Apart from hanging nets, form-finding (of pure shells) can also be conducted mathematically/ computationally. The most efficient form of load-bearing behaviour is recognised through complete compression membrane stresses without bending i.e. as proper shells. Bending stresses (prevalent in improper shells) implied weakness to the shell and may cause the structure to fail or collapse completely.

However, traditional modes of form-finding do not answer questions about the optimisation of construction process, efficiency of labour and economy of formwork. It excludes the assertion of the designers' aesthetical values or visual judgment. In the true sense of form-finding, mechanical statics is recognised as the primary governing factor in arriving at structural forms with maximum structural efficiencies. It is important to note that the regard of aesthetic and spatial requirements is an important point of consideration in shell form-finding as well.

The acknowledgement of this architectural and constructability dimension is critical. When the designer (e.g. architect) uses form-finding tools to design shells, can he/ she also integrate spatial concepts/ requirements (e.g. building areas, heights and other physical dimensions) together with structural concerns? If so, how does the designer (e.g. architect) use this process to enhance their structural imagination and architectural creativity? If the designer has no control of the shapes of the shells, the architecture program may suffer in terms of quality as functional requirements may be compromised by purely form-finding.

Over time, formfinding processes have improved in sophistication and accuracy. It can also be carried out computationally through processes such as dynamic relaxation. With powerful computer softwares such as OASYS Arup and TNA (Thrust Network Analysis Block, 2011), structural efficiency through morphology can be exercised materially through masonry and concrete. The computerised method replaces the laborious use of complex mathematical equations and/ or physical models. However, form-finding in virtual space does not provide the designer with a qualitative understanding of force and material interaction.

One key problem the process of form-finding encounters is the missing gap between form-finding stage and construction process. Although it is possible to design forms of near perfect load paths i.e. pure compression, their construction presents new challenges. We see this in the limited use of bespoke glulam timber trusses formwork used to construct Heinz Isler’s concrete shells. Although reusable, unfortunately, they have little reconfigurable potential to achieve shells of variable geometries. This limitation will be discussed further in chapter 3.9.

3.2.3 Shell Geometry

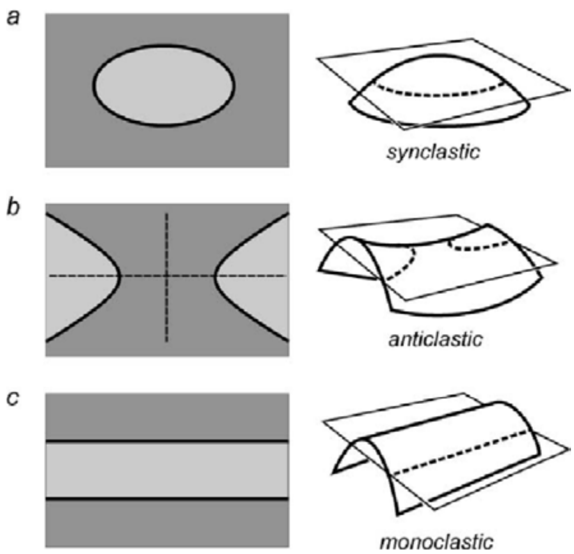


Fig 3.10 a) synclastic b) anticlastic and c) monoclastic geometries (courtesy of Lisle, 2003)

Since shells depend so much on shapes, the understanding of shell geometry is important. Surface regions of Shells can be described by their geometry and shell geometry can be classed in three ways:

3.2.3.1 Synclastic shapes: where the revolution of a curve is on the same side, examples of these include domes. To maintain the dome shape, hoops or compression rings can be installed. In shells, these are described as hoop forces.

3.2.3.2 Anticlastic shapes: where the revolution is on the opposite side. They are usually saddle shaped as exemplified by Candela’s church at Cuernavaca, Mexico.

3.2.3.3 Monoclastic shapes: barrel shapes where the curve is extruded on a straight line. These are expressed as singly curved vaults.

3.2.4 Structural Truths: Shell-like structures which are not actually shells.

3.2.4.1 Aquatic Centre, London (2012) by Zaha Hadid

Fig 3.11 The form of the London Aquatic Centre roof, inspired by the aqueous geometries of wave forms in water suggests a shell structure. (credit: Hufton + Crow)

The London Aquatic Centre, designed by Zaha Hadid is widely recognised by the doubly-curved roof bearing close resemblance to a shell. However, beneath the surface reveals a complex matrix of structures. The curved surface is, in fact, not a thin shell but was created from a complex system of steel trusses/ frames supporting a non-load bearing sculptural surface described in fig. 3.11 and 3.12. (King and Mungall, 2012).

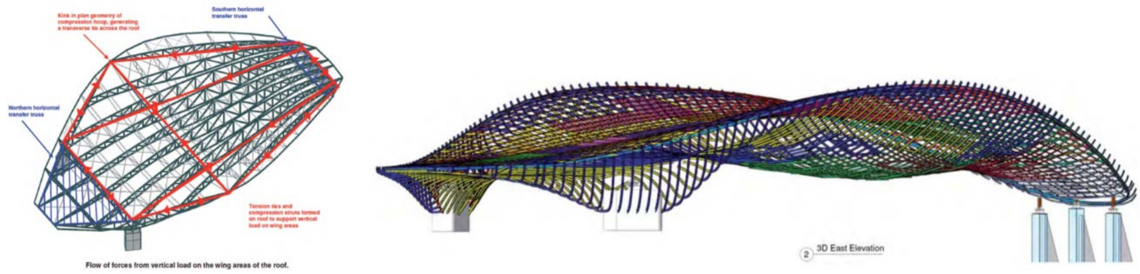


Fig 3.12 The hidden structure of the "shell-like" aquatic centre.

3.2.4.2 Enzo Ferrari Museum Roof 2012

Jan Kaplicky, Future Systems

Similarly, the roof of the Enzo Ferrari museum roof by Jan Kaplicky also resembles a shell. Doubly-curved, shiny and yellow, the roof is also constructed of a series of steel trusses that is clad with powder-coated aluminium tongue and groove planks avoiding the need for expansion joints. The structure is supported on a steel truss lattice with 4,000 metal node-to-rail connections allowing a complete movement of this surface (Wainwright, 2012)

Fig 3.13 The yellow aluminium roof of the Enzo Ferrari Museum 2012 designed by Jan Kaplicky and finished by Studio Shiro following Kaplicky's death is a shell-like structure which is supported by steel trusses. *(*copyright Foundation Enzo Ferrari)

Increasingly, due to advances in fabrication techniques and cheaper material use, as well as rapid structural analysis, non-structural double-curved surfaces can be manufactured easily. The Ferrari Museum and Aquatic Centre stand as cases where this possibility have resulted in the creation of structures that resembled shells, but are not structurally so, by definition. This interrogates the notion of structural truths and the honesty of structure.

Fig 3.14 Interior of the Church of San Antonio de las Huertas, Mexico City by Felix Candela 1956 celebrates the straight planks and plasticity of concrete, painted first in white paint, then painted over by coloured light.

3.3 PROPER SHELLS

A Brief History of Thin Concrete Shells since 1900.

The following section gives an account of the development and rise in concrete shell popularity, critically describing milestones of means and methods of construction developed by key shell builders resulting in seminal projects in the history of concrete shells.

3.3.1 The Rise of Concrete Shells

The development of doubly curved surfaces is closely associated with the development of vaults and domes. Bechthold (2008 p 27) accounted the evolution of such structures featuring the extensive use of temporary props and scaffolding that held up centring before being removed after concrete pour. Cheap post-war labour was also plentiful and met the demand. Development in concrete shell technology accelerated at this time as concrete shells captured the architectural and structural imagination. It was a time when other materials such as metal and timber were scarce. Concrete had to replace other building materials during a time when constriction material was scarce and labour cheap.

In memoriam to the life and work of the late Felix Candela, Cassinello et al (2010) expressed the sentiment that the heyday of concrete shells was deemed the result of the work and development of nine prolific shell designers: namely:

1. Eduardo Torroja (1899 -1961)
2. Felix Candela (1910-1977)
3. Robert Maillart (1872-1940)
4. Pier Luigi Nervi (1891-1979)
5. Heinz Isler (1926-2009)
6. Franz Dischinger (1887-1953)
7. Ulrich Muther (1934-2007)
8. Anton Tedesko 1904-1994) and
9. Eladio Dieste (1917-2000).

Sadly, the memoriam also attributed the diminishing of this movement to the passing of these masters with the exception of Heinz Isler who had a successful career in designing and building concrete shells in the 70s extending into the 90s, a note-worthy exception.

The growth of materials such as steel and the impact of the high tech movement also changed the way these structures were viewed. The role formwork remains an important factor to the development, acceptance and eventual rejection of the typology to be discussed in Chapter 3.4.

3.3.2 Development and Advancement in the concrete shell construction at the turn of the century (1900 onwards)

The section below highlights the improvements and the quest for shell thinness and simplified concrete shell construction system, aimed at minimizing construction time, complexity and the amount of concrete used.

3.3.3. Shells of simple geometry and the innovation of a construction method

The first engineered concrete shell date can be traced back to Jena Planetarium of 1922 which is still in use today (https://structurae.net/structures/zeiss-planetarium). The shell is a synclastic dome which spans 25m and 6cm thick (giving a thickness to span ratio 0.24%). The project was the winning design by Franz Dischinger of Dyckerhoff & Widmann for the Zeiss factory which manufactured precision optical equipment. As the planetarium was positioned on top of an existing roof, the structure had to be light-weight. It was constructed by spraying concrete over a mesh placed on top of a steel framed geodesic structure. Allegedly, the geodesic structure was inspired by illustrations of botanical micro-organisms. 3480 steel rods (*Flacheisenstabe*) each 600mm long formed the geodesic structure (Addis, 2008). The stiff structure famously withstood point loading from workmen who stood on or clung from the frame (fig. 3.15). The steel grid was embedded within the concrete to form a concrete hemisphere which became a synclastic surface onto which light shows were projected. To prevent concrete from passing through this frame, a movable timber formwork was placed behind, in a method known as the *Tokret.*

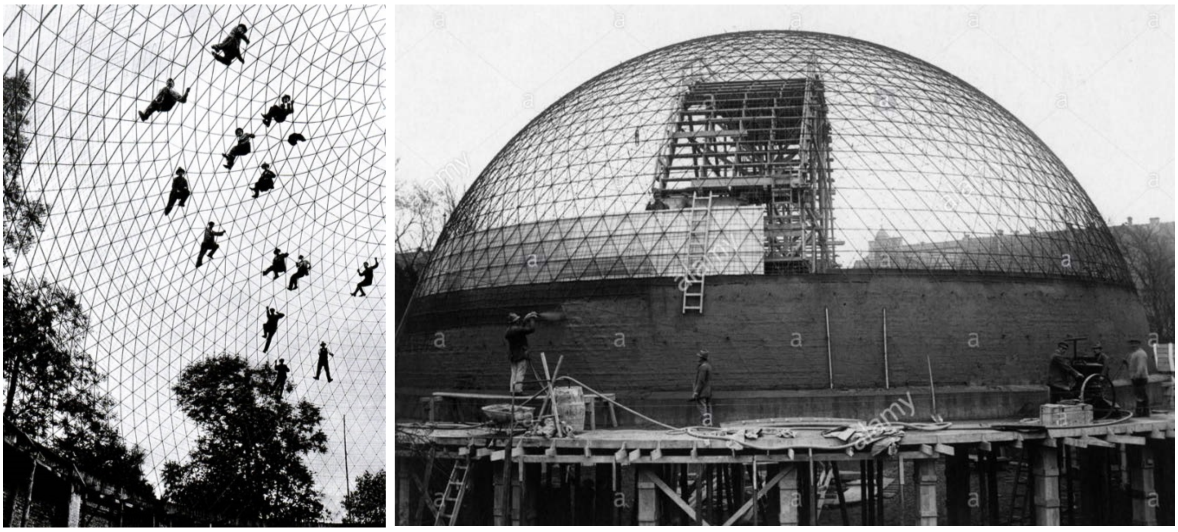


Fig. 3.15 Walter Bauersfeld, Dyckerhoff & Widmann. Planetarium, Jena, Germany, 1924-1925.
Copula netting during construction. (http://www.all-art.org/Architecture/25-5.htm)

With advancement by this new method, reinforced by advances in mathematical theories of thin concrete shells, Dischinger received academic recognition for his theoretical work. Although the ZD method produced thin reinforced shells, the framework was embedded within the concrete build-up. The doubly-curved smooth surface, although perfect for the purpose of astronomical projections, concealed an intricate network of steel structure acting as the primary structure.

When this technology was brought to the United States by Anton Tedesko, a Dwiddag engineer, timber replaced the steel members due to unavailability. His work at the Hayden Planetarium in New York (1935) and the exhibition pavilion at the Chicago World Fair (1933) renewed interests of concrete shells in United States (Hines & Billington, 2004). Anton Tedesco was braver and more experimental in his design approach. Hines and Billington expressed relief that,

"Dischinger was more analyst than designer. Fortunately, it was Dischinger's propensity for combining analysis, structural testing, and construction rather than his love of complicated math that influenced Tedesko." (Hines and Billington 2004).

Hines and Billington (2004) were critical on the early approaches of concrete shell design, suggesting the early German designers were too mathematical in their approach for they only designed what they could calculate at that time (Billington, 1983). This reliance on mathematical theory is limiting. Unleashed from the shackles of mathematical analysis, later shell builders, including Heinz Isler and Felix Candela, produced shells which were judged more visually pleasing (Hines and Billington 2004, Billington 1983 pp171-193; 213-232).

3.3.4 Aesthetic consideration vs construction ease/ cost.

The most impressive work by Anton Tedesko was his roof for the Hershey Arena (1936) designed for the chocolate industrialist, Milton Hershey spanning 68m with a thickness of 8.9cm (thickness/span 0.13% which was almost twice as thin as Jena Planetarium).

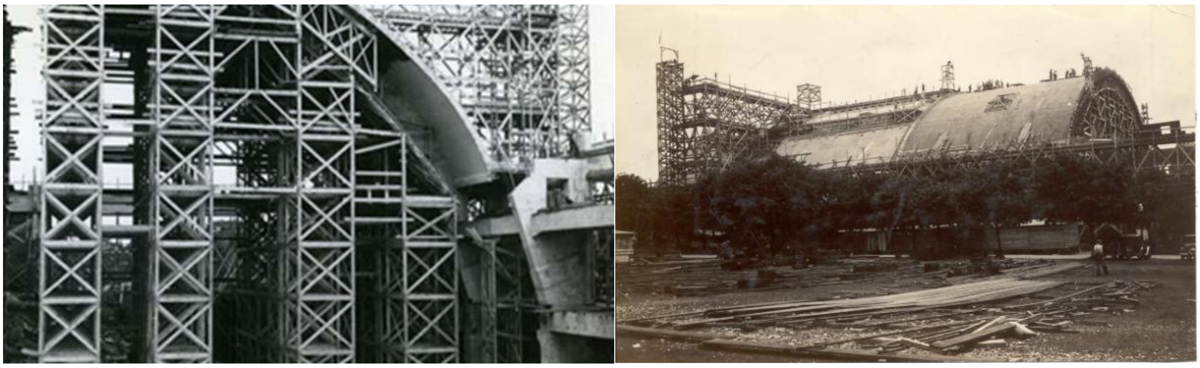


Fig 3.16 (left) Rolling supporting towers that rolled down the length of the Hershey Arena Shell. (right) Construction from outside (http://anengineersaspect.blogspot.co.uk/2009/06/history-of-thin-shells-and-monolithic.html)

Having no access to the precise formworks of Zeiss only available in Germany, Tedesko used timber falsework instead. These were affixed on a rolling system where timber falsework rolled lengthwise along tracks to produce mono-clastic shells (chapter 3.2.3.3.). Tedesko's contribution to concrete shell innovation was the simplification of formwork system and construction method, shortening construction time and cost. To accelerate construction speed, reinforcing ribs were eliminated; challenging Dischinger's original mathematical assumptions. Using this system, he proved that ribless shells could be constructed. This move was driven by the desire to build quickly. According to Hines and Billington (2004), "by 1950, Tedesko's work in America generated several million square feet of American thin shells and two major innovations : the ribless shell and the wide-spanning short barrel shell".

The need to build has transformed the evolution of concrete shells in design and construction terms. In equal importance is the motivation to design beautiful shells. As the development of shells progressed, aesthetics became important. The Spanish shell designer Torroja famously said,

> *"Economic factors add nothing to the aesthetic values. The best structures do not have to be the cheapest."* (Torroja 1958 p327).

Torroja's starting point in design was focused on aesthetics. With structural intuition guiding an approach aimed at producing structurally expressive forms, he broke away from the restrictive mathematical approach discussed earlier.

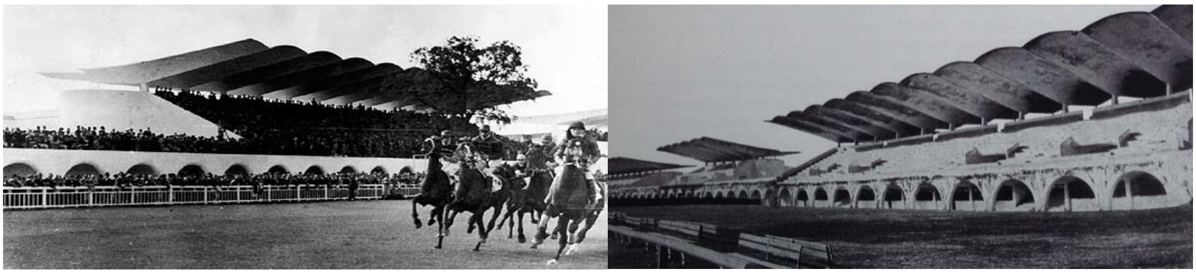


Fig 3.17: La Zarzuela Race Track (1935) by Eduardo Torroja

One of the most iconic structures by Torroja was the Madrid Hippodrome (1935), also known as the Zarzuela Race Track. It had a shell roof cantilevering 14 metres forward from the main support and 7.7 metres backwards. Resembling the Roman fabric awning which donned the Coliseum in Rome, the steel reinforced concrete shell was balanced on central supports to offer protection over the seats of the outdoor race track. A 4.8 cm thick free edge (giving an edge thickness to span ratio of 0.34%) lent the shell an air of visual lightness. Torroja was keen to emphasise this thinness and adjusted the design to ensure this was expressed. However, a detail not detected by the human eye was the way the roof thickness increased to 14cm at the crown over the line of main supports. Torroja demonstrated his understanding of the relationship between structure and aesthetic by tapering the shells towards their edges to express thinness whist thickening support points to offer stability. To work out structural behaviour, before the advent of computerised structural analysis, Torroja famously investigated the behaviour using a card model to inform steel reinforcement bars patterns (Billington, 1983). The use of steel ring reinforcement hidden within the shell roof brings the issue of structural honesty of structural function of shells into question. Clearly, these shells had bending moments and required extensive reinforcement design to "correct" these non-compressive forces. This questions structural purity and the aesthetic values placed on creating a false impression of shell thinness!

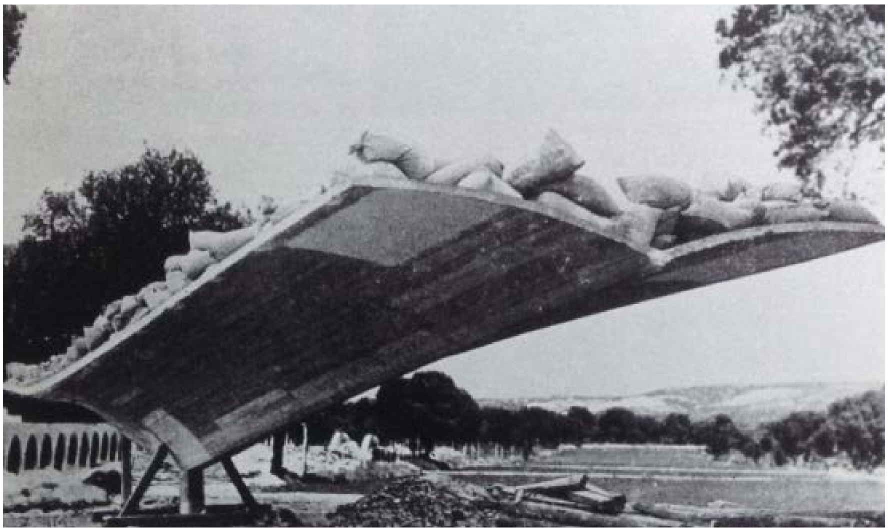


Fig 3.18 Prototype load testing of a single bay of the Zarzuela Roof.

Steel reinforcements were laid within the concrete in concentric rings (fig 3.19). Concrete was cast over a timber formwork formed from straight planks.

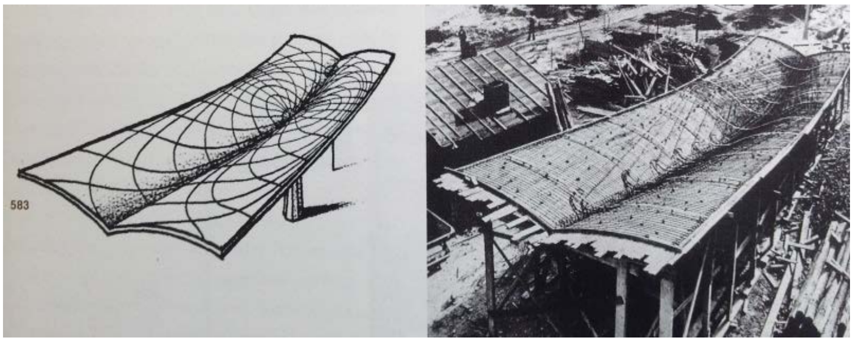


Fig 3.19 Stress lines derived from paper observation. Reinforcement rings are visible before being embedded in the proceeding concrete pour.

Another seminal concrete shell project by Torroja is the roof for the Fronton Recoletos Jai-Alai Court in Madrid (1935). This was an extruded double-lobed form spanning between two side walls. The cylindrical shells have a radius of 6.4 and 12.2 m which together spanned between side walls 55m apart (fig. 3.20). The clerestory allowed natural daylight to enter the sports hall from above. The concrete shell was 80mm thick (giving an thickness to span ratio of 0.34%) with the exception of the centre section of 150mm where the two sections joined together (with thickness to span ratio of 0.64%). Again, to verify and study the structural behaviour of the roof, Torroja built and tested a 1:25 scale model. Although the roof was built as a thin-shell, it was effectively acting as a vault (Pedreschi, 2010). Unfortunately, this building collapsed caused by damage during the Spanish Civil War (1936-1939).

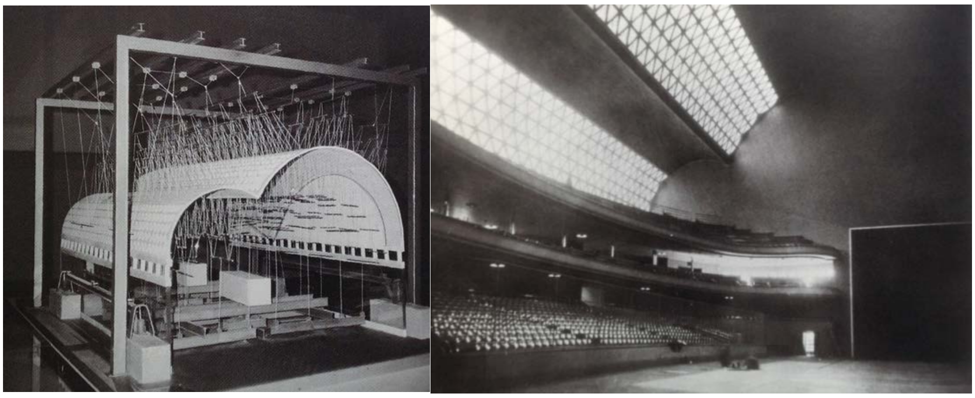


Fig 3.20 (top left) Model testing of the Fronton Recoletos, Madrid. (right) Fronton Recoletos, Madrid completed and used for the traditional sport of peletos http://tecnomadas.wordpress.com/2009/11/07/fronton-recoletos-la-creacion-del-espacio-continuo/

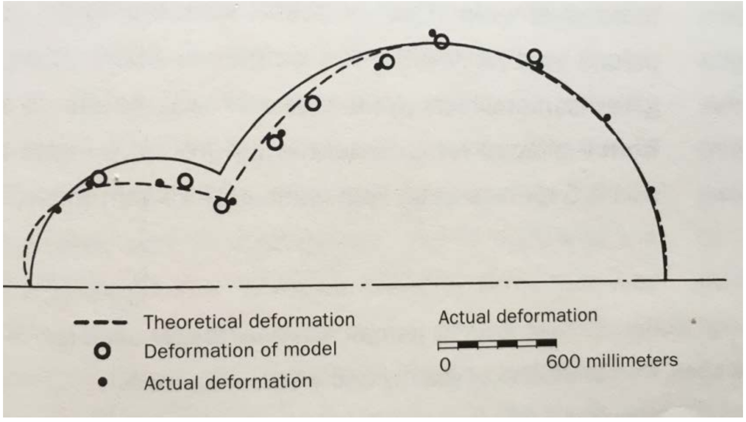


Fig 3.21Comparative deformations of the roof (1935) (Taken from Addis, 2008)

Clearly, shells were developing in structural complexity and visual sophistication with each successful shell design/ construction constructed, adding confidence to the construction of concrete shells.

Being cheaper than steel, the world wars saw a scarcity of building materials resulting in the widespread use of concrete, With labour cheap and plentiful, concrete shell construction quickly gained popularity. A lack of metal and timber employed in artillery played a major role in motivating Nervi to combine pre-cast and cast-in-place concrete to build cheaply and quickly.

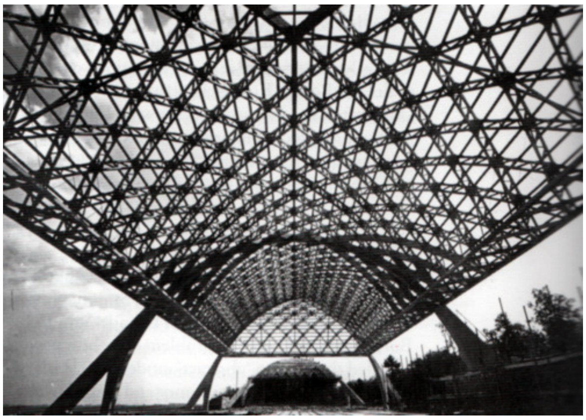


Fig 3.22a (left) Orvieto Airport Hangar   Fig 3.22b (right) Geodetic Frame of Hangar made from pre-cast reinforced concrete trusses. (http://en.structurae.de/structures/data/index.cfm?id=s0000050)

3.3.5 Shells created from pre-cast components

Whilst aesthetics drove Torroja's work as a shell innovator, economy stands as a prime driving force in the works of Pier Luigi Nervi (Billington, 1983 p178). His background in building was developed through his work as a contractor where he ran his construction company- Nervi and Bartoli, with his cousin. The search for a cheaper, easier and faster way to build was instrumental to his innovations.

Nervi was commissioned to design and build aircraft hangars in Orvieto, Italy. This began with a geodetic structure which served as a testing field for shell component pre-casting. He observed that to build the aircraft hangar using traditional timber formwork was expensive and time-consuming. To cast a shell in situ was formwork-intensive, as concrete had to be poured at height into complicated formwork which had to be constructed/ pre-fabricated as well.

To shorten construction time, Nervi broke down the rib shell into identical panels and cast them on the ground. Produced under shelter, workers moved these pieces (known also as *travelloni)* into position supported by temporary supports. Pre-casting individual panels on the ground shortened the time required to build. This also meant that concrete sections could be constructed indoors and be produced even in bad weather. One weakness of weather dependency was dramatically demonstrated by Tedesko's Hershey Arena construction when storm waters caused part of the uncured shell to slide away catastrophically during the first cast (Hines and Billington, 2004).

The impact of Nervi's innovation also meant that the identical units could be repeatedly produced and used almost anywhere on the shell. This innovation responded to cost concerns. The precast panels were also uniform and modularised. The joints between pre-cast panels were formed by "stitching" panels together using reinforcement bars which were cast to protrude out from the *travelloni* edges. When placed in position on temporary scaffolding, quick-setting concrete was used to cement these individual sections together.

Nervi manipulated material (concrete) to invent a novel hybrid system that embodied both speed and beauty – allowing beautiful efficient structures to be built quickly. In his quest to address constructional cost, architectural aesthetic, material economy and structural efficiency, this construction system revolutionised the way shells were built.

Nervi also invented *ferrocemento* in the early 1940s. Ferrocemento is concrete with fine pliable steel mesh embedded within made by applying concrete until the supporting mesh is saturated and appeared on the other side. This elastic, flexible and highly resistant material measured only 3cm at its thinnest, crucially making formwork unnecessary (Lori, 2009). In his own words, Nervi pointed out that *ferrocemento* could "stand great strains without cracking, and because of its superior strength and elasticity, it can be used in exceedingly thin slabs and shells. In many instances, formwork could be avoided because the cement mortar can be applied directly to the shaped mesh, just as plaster is to a metal lath" (Huxtable 1960).

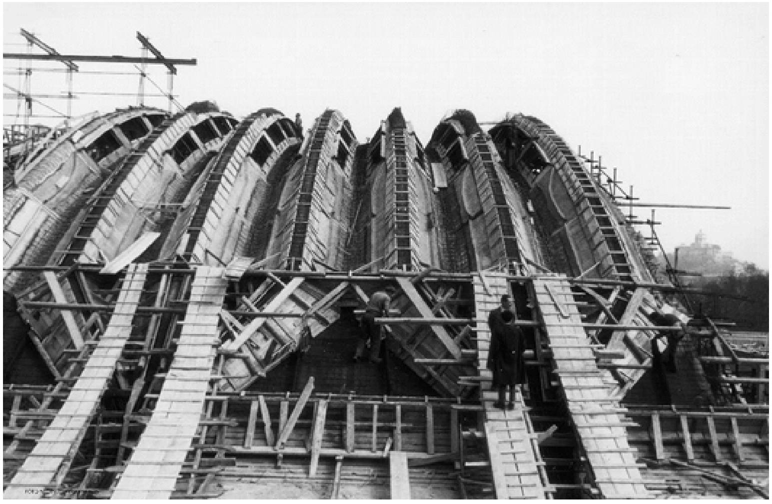


Fig 3.23a (left) The internal precast roof panels inset with glazing.
Fig 3.23b (right) The Nervi'rian method in operation for Salone Agnelli, Torino, Italy.
http://www.domusweb.it/en/from-the-archive/turin-exhibition-palace/

Huxtable (1960) proclaimed that "This free prefabrication of parts and consequent expansion of usable structural shapes changes the whole concept of reinforced concrete construction." This is very true even today. Four decades on, this concept is still used to achieve rapid component assemblies to reduce time, hence cost, to bring about an economical solution in concrete even today. The Italian architect Vittorio Giorgini (Chapter 3.2.1.2) and the USSR Soviet bus-stops published in Hewig (2016) discussed earlier were concrete structures produced this way.

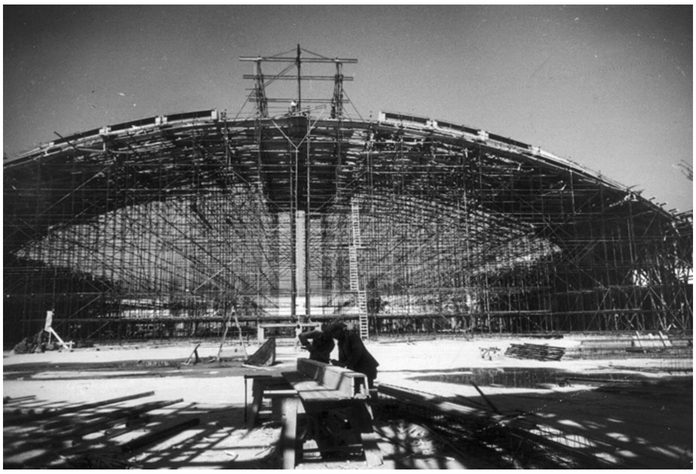


Fig 3.24 Rolling scaffolding towers to provide support and speed of erection.
http://www.domusweb.it/en/from-the-archive/turin-exhibition-palace/

Nervi then applied this idea of pre-fabrication to the Exposition Halls B (Salone Agnelli) in Torino, Italy in 1948. The halls were built after the war as a series of great halls to promote trade and commerce in Italy. The 2213 square meter of space was quickly and beautifully roofed in a short period of just ten months, bearing testament to the effectiveness of Nervi's method. The Salone Agnelli was composed of two geometric parts: the first consisted of a vaulted central nave 90m wide, and the second, a semi-circular apse at the end of the hall. The barrel vault spanned 80m with a length of 100m. One end had a semi-circular apse, 60m in diameter using a method Nervi developed in the winter of 1944 (Garlock and Billington, 2008). Nervi said:

> *"The process (is) effective from a technical and economic point of view and resulted in great plastic richness."*

The first system, described as "waves" was made from pre-cast ferrocemento panels laid side by side and only 3 cm thick and cross-connected by diaphragms over temporary and moving scaffolding. Similar to Tedesko's American models, this rolled down the length of the construction. At the sides, a trio of waves were picked up by an inclined pylon that widened toward the ground and transmitted the load into the foundations. This arrangement of pre-cast panels allowed glazed openings insets within the structural pre-fabrication system to allow natural daylight to pour into the space from the top. The semi-cupola was constructed out of diamond-shaped pieces (*tavelloni romboidali*). These were also cast on ground and raised to position. This idea was widely regarded as the precursor to his signature work - the Palazetto dello Sport in Rome built for the 1960 summer Olympics.

Billington (1983, p180) calls The Palazetto dello Sport (1960), Nervi's "greatest masterpiece". It is a cupola constructed out of a radiating *tavelloni romboidali* developed earlier. Structurally, it was a good idea as not only do the two sets of ribs intersect to form an elegant pattern, the ribs also allowed the shell to become stiffer without becoming heavier, referencing to the coffered roof of the Pantheon (Billington 1983).

Nervi used repeated elements and standardised construction system to economise construction. This method of construction changed the appearance of shells. Instead of having smooth undersides, the new shells developed a rich sense of the construction process and expressed shell force lines. These shells enclosed space efficiently, but gave the structure tectonic (that exhibited their construction method) not seen previously. The technique fused the ribs and skin into one monolithic construction but showed their components.

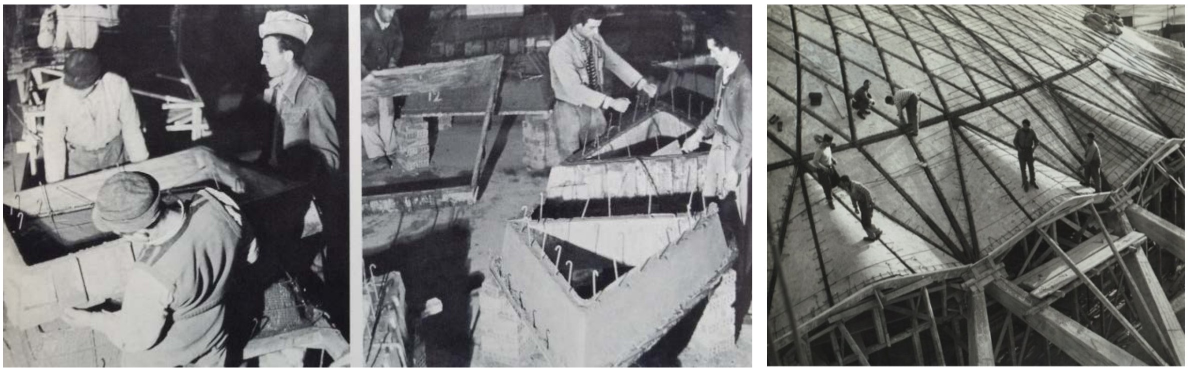


Fig 3.25 (left and centre): Precasting the tavellonni on the ground. (right): Assembling the pre-cast panels by stitching the concrete tavelloni using quick-setting concrete. http://techniker.oi-dev.org/blog/view/engineers-cowcross-gallery-talk

Undoubtedly, economy and construction efficiency were prime philosophies in Nervi's approaches to construction technologies. In fact, Nervi admitted that he could build because he was the cheapest (Nervi, 1965)! Clearly, Nervi's approach was different from Torroja's. Written as part of the Harvard Charles Elliot Norton Lectures, in his book, Aesthetics and Technology in Architecture (1965), he recounted:

> *"When I approach a project, my first instinctive thought is to reject the solutions which, even at first glance, do not seem to me to be economically valid. To search for an economic solution in the structural field means to find the most natural and spontaneous solution or, in other words, to find the method of bringing dead and live loads down to the foundations in the most direct way and with the minimum use of material."*

Maverick, non-conformingly, but structurally radical, Nervis' design philosophy was admirably refreshing. He said structures "can only be solved correctly through superior and purely intuitive re-elaboration of the mathematical results" (Nervi 1956, Structures). Explorations of form and mathematical analysis did not faze or restrict the designer from creating structures of beauty, structural logic, material and cost economy.

This eye for beauty and his uncompromisingly practical approach breathed new life into concrete shell building. By breaking down the concrete shell into repeated elements, Nervi was able to create double-curved shell structures from geometric pre-cast concrete elements. Importantly, Nervi's contribution ties shell form and the construction process together to bring about cost economy and time efficiency.

3.3.6 Creating Curves from Straight Elements

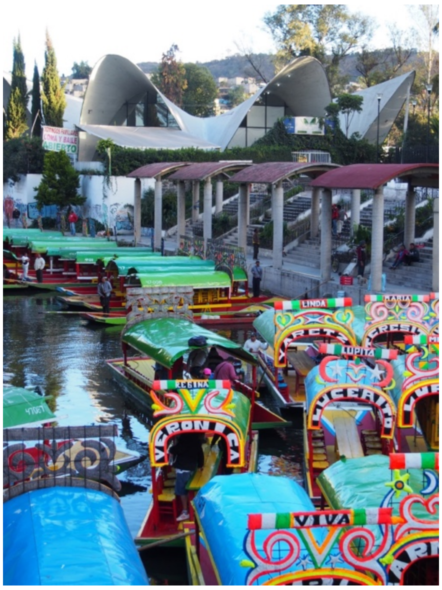



Fig 3.26 a (left) Constructing the Cosmic Ray Pavilion, Mexico City. (Copyright: Gabriel Tang)
Fig 3.26b (right) Los Mantiales restaurant at Xochimilco, near Mexico City. (Copyright: Gabriel Tang)

Curves in shells could be created by casting concrete onto a formwork of geometrically arranged straight planks. At a time of technology without computers, the Spaniard, Felix Candela, exiled in Mexico, was able to build shells by using straight planks through the use of hyperbolic paraboloids to create double curvatures. He was able to use this understanding to simplify formwork to achieve economy with ease.

3.3.7 Testing by Building

In 1949, Candela built a funicular Ctesiphon Vault at San Bartolo de Naucalpan, Mexico, largely inspired by James Wallers' ideas (chapter 3.6.1.2) on shell construction (Faber and Candela 1963, p16). From then onwards, Candela built experimental shells to test their structural behaviour and this quickly became his signature way of studying and understanding shell structural behaviour. Again, the low cost from the Mexican labour force provided fertile testing ground. He believed that his ability to build concrete shells differentiated him from other practices in the highly competitive construction industry in Mexico at that time (Faber and Candela, 1963).

Candela experimented with building a conoid measuring 15m by 6m and about 2.5cm thick. A timber formwork was constructed upon which timber planks were laid. He had supported the forms on boxes of sand to make the decentring process uniform. Unfortunately, due to the concrete being too dry, the concrete got stuck to the form and had to be knocked out from it with force. Through this process of building, Candela learned that in this case, “the minimum thickness for a shell, from a practical and economical point of view, was 4 cm.” Secondly, in large shells care must be taken with decentring, but normally forms could be removed from the sides or from the centre of the structure, keeping in mind the symmetry of the design (Faber, 1963). His method of experimenting with shell construction is similar to the experimental constructions of engineers like Robert Maillart who understood material behaviour and process through the process of constructing prototypes. Maillart was influential on Candela’s work and ideas through his reading about his work. Maillart’s papers introduced Candela to simplified calculations rather than just rigorous analysis, an approach which he found “delightfully sympathetic and encouraging” (Garlock and Billington 2008).

Candela first rose to international imminence after his design for the 1951 Cosmic Ray Pavilion was realized for the University of Mexico (Garlock and Billington 2008). For this building designed to measure celestial rays, the University required that the roof thickness be less than 1.5cm at the apex to allow cosmic rays to be measured from within the pavilion. He used straight boards for the dovetailed timber formwork of this thin concrete shell to build hyperbolic paraboloid shells. Similar to James Waller's Ctesiphon vaulting, the "corrugation" and curvature in the saddle form not only gave his shells extra stiffness, it also made the doubly-curved form buildable from very basic materials composed of straight timber planks instead of Waller's Nofrango Method which made use of cement soaked hessian (Conlon, 2012). James Waller's work will be discussed in detail in Chapter 3.6.1.2.

One of his most representative works is his 1958 Los Manantiales restaurant at Xochimilco, near Mexico City. Composed of 8 hyperbolic paraboloid vaults radiating from a central point, the building appears thin at the edges of the shell see fig 3.27). It spans 42.5metres and yet was just 42mm thick (giving thickness to span ratio of 0.1%). With the glazing set deeply within the eaves of the roof, it offered an uninterrupted space for social gatherings or religious congregations.

Fig 3.27 The exterior of the Los Mantiales Restaurant by Felix Candela 1958 (Gabriel Tang)

Fig 3.28 The internal surfaces of the Los Mantiales Restaurant by Felix Candela 1958 (Gabriel Tang)

Candela's approach to design was grounded on geometrical understanding. His shells prevailed in Mexico because they were cheap and beautiful with a thinness made possible by the mild climate. Candela's shells began with shapes, which through repetitions and permutations, opened up form possibilities of smaller repeated hyperbolic paraboloid sections to compose and form roofs. Often repeated with articulating gaps between shells to form the design, Candela's designs allowed light to penetrate the space enclosed, avoiding the need to puncture the surfaces to illumination and acoustics effect not seen previously.

Nervi used hy-par (hyperbolic paraboloid shapes) extensively in his designs. These are ruled surfaces with a concave form on one surface and convex in the other. These doubly ruled forms could be constructed from straight-lines and could be used in the construction of curved surfaces.Significantly, his meant that by using simple straight planks, geometrically complex but structurally efficient hy-par forms could be achieved.

3.3.8 The Hyperbolic paraboloid Form

> *"of all the shapes we can give to the shell, the easiest and most practical to build is the hyperbolic paraboloid." Candela in Faber, 1963*

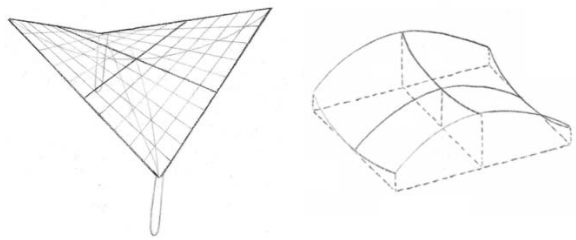


Fig 3.29 (left) a: Hyperbolic Paraboloid Geometry – straight line generation; (right) b: Hyperbolic Paraboloid Geometry – parabolas of opposite curvature. (sketches copyright of Rachel JE Sprague).

Felix Candela used hyperbolic paraboloid geometry extensively in his work.

Hyperbolic paraboloids are doubly curved surfaces produced through translations and rotations of straight lines. They are commonly defined in two distinct ways: first, by warping or twisting of a 2-D plane; alternatively, by the translation of parabolic arcs along a second hyperbolic arc of opposite curvature (fig. 3.29b and 3.30). In both cases the surfaces have negative Gaussian curvatures, i.e. having principal curvatures of the opposite signs. The form is most easily identified as a saddle-shape (Sprague, 2013).

Many of Candela's structures are variations of the hy-par (hyperbolic paraboloid). Felix Candela was able to vary their architectural expression to create a variety of building through creative permutation, re-composition and repetition of the hy-par. By changing the edges, he also managed to vary their architectural expression. He used both curved and straight edges to differentiate the shell designs.

The fact that these double-curved geometries can be achieved with straight lines allowed Candela to form curved surfaces using straight planks (Lee and Garlock, 2010).

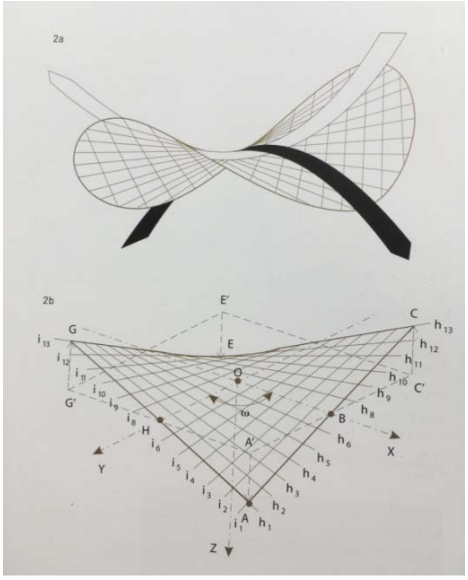


Fig 3.30 (top) Hyperbolic Paraboloid with curved edges (bottom) with straight edges. (courtesy of Garlock and Billington, 2008)

The two examples below showed how Felix Candela made use of the hy-par unit to compose churches.

a) Church of San Antonio Huertas, Mexico City (1956).

The church is composed of three free-standing groined hy-par vaults. These are separated with a gap between the shells to allow light to enter and colour the internal spaces.

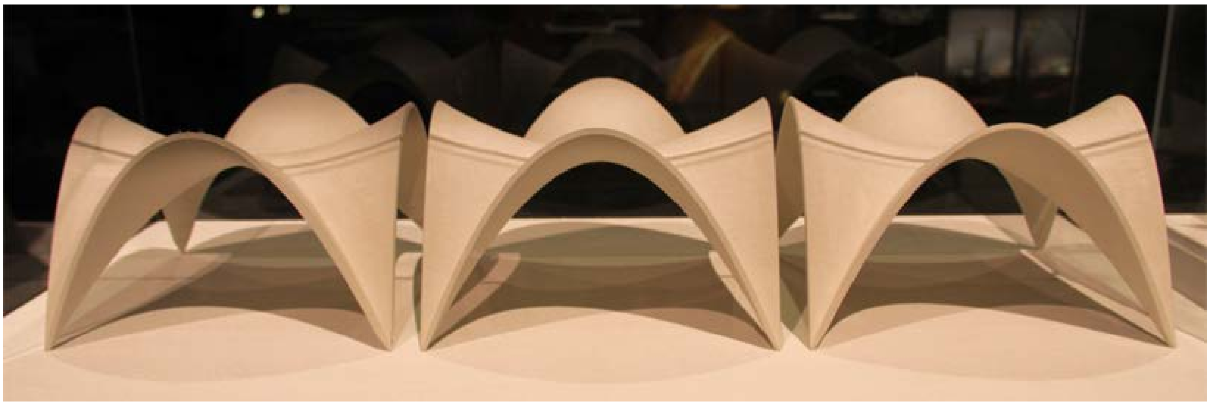


Fig 3.31 Scaled plaster model of the Church of San Antonio, Mexico City (1956) that illustrate its structural concept. (copyright Designboom.com)

Fig 3.32 Church of San Antonio, Mexico City (1956) (Gabriel Tang)

b) San Vincente de Paul Capella, Mexico City (1960)

This church is composed of four hy-par concrete shells positioned together and pivoted about four abutment point supports as illustrated in fig. 3.33. Again, the concrete shells are articulated and separated with glazing sections to allow light to penetrate the space within.

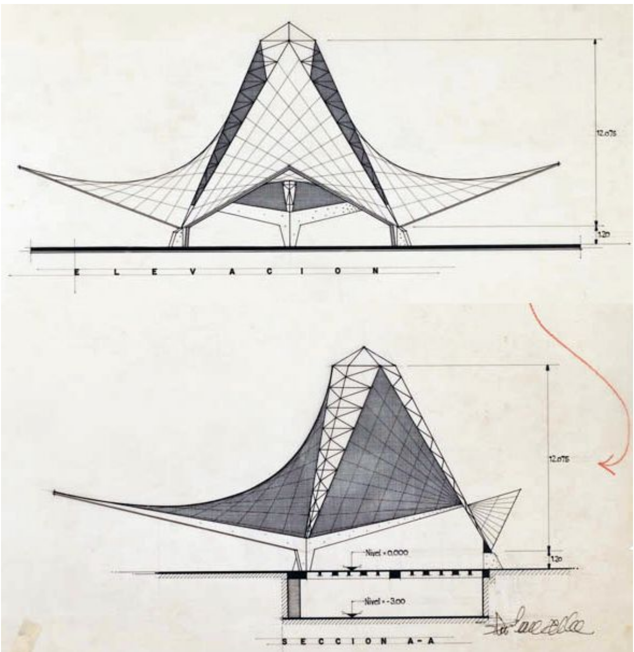


Fig 3.33 Elevation drawings. Light is allowed to pour into the building space from articulated strip glazing between smaller shells. San Vincente de Paul Capella, Mexico City (copyright Felix Candela Archives)

Fig 3.34 Interior spaces of San Vincente de Paul Capella, Mexico City (Gabriel Tang)

Fig 3.35 Exterior San Vincente de Paul Capella, Mexico City (Gabriel Tang)

3.3.9 Heinz Isler

Heinz Isler (1926-2009) was a prolific designer of concrete shells. Born, raised and worked in the temperate Switzerland, he designed and built numerous concrete shells.

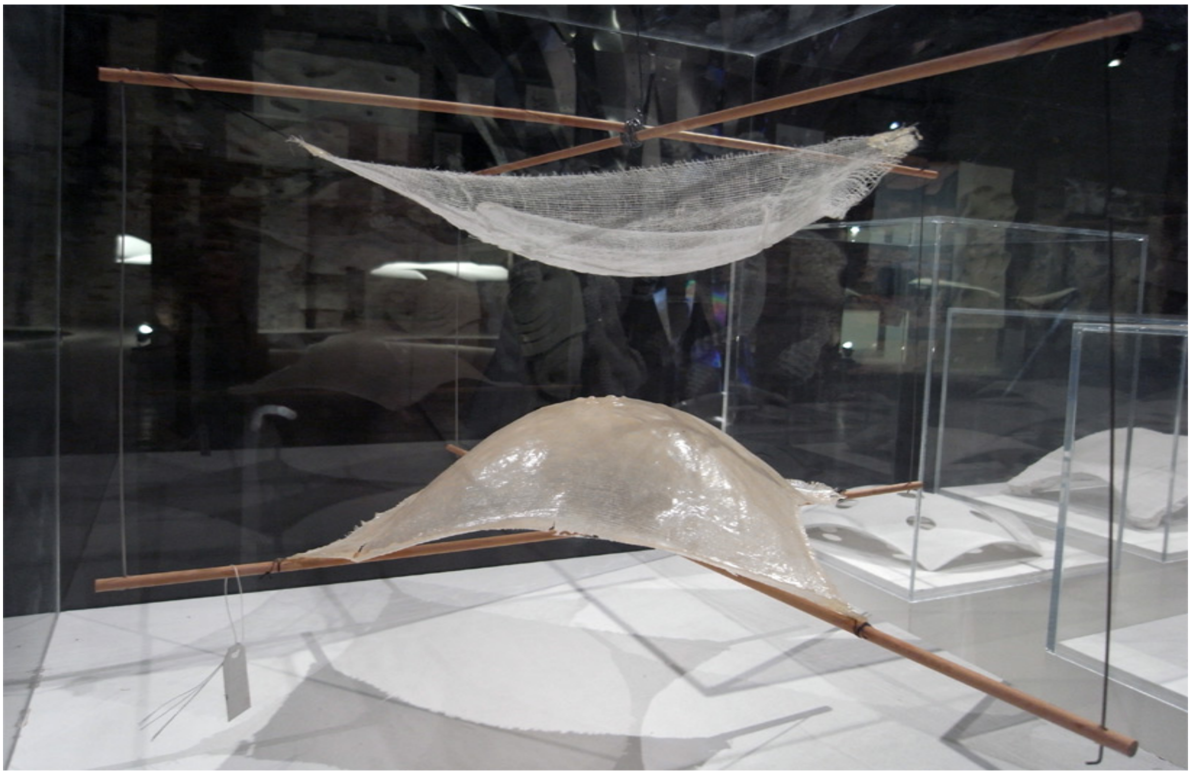


Fig 3.36: Hanging cloth study model of wood, fabric and string by Heinz Isler image (copyright designboom)

Fig 3.37 Repeated shells using same formwork system to achieve economy. Heimberg Tennis Center, Switzerland. (Anderson, 2004: p.103) (copyright http://shadesofgreendesign.com.au/biomimicry-structural-lessons-from-orchid/)

A structural engineer by training, his work largely involved experimentation with physical models to inform the form-finding process. Isler was most remembered for the use of hanging membrane models to form-find his “inverted membrane shell series” illustrated by fig.3.36. By hanging a membrane impregnated with resin, perfect shell shapes (proper compression shells) could be derived as explained in Chapter 3.2.2 (Chilton, 2000, Addis 2008, Addis 2013, Azagra and Hay, 2012). As well as inverted membrane shells, he also produced “compression bubble shells” based on the principles of inflating a membrane stretched onto a frame (Chilton, 2000).

Isler’s shells were inspired by observations of nature, with a curiosity in material statics, an approach of child-like experimentation he described as “creative play” (Chilton, 2000, p28). His concrete shells were constructed differently from the way they were form-found. Concrete was laid onto a matrix of prepared timber glulam falsework supported by scaffolding. Specifically, his bubble shell series had a regular geometry and were often repeated. As such, the formwork could be reused easily. For his inverted free-form shells, formwork was specialized, bespoke and included numerous trusses defined by complex geometry. Tailored to realise bespoke concrete shells, many of these formwork were only used once, making them less economical than conventional construction. Fortunately, over many years, Isler built up good working relationships with specialist contractors and as a cost measure, was able to retain and use them again when the same shell geometry was built.

3.3.10 Ulrich Muther

Muther constructed shells by pre-fabricating them in sections to avoid costly formwork. An entrepreneurial East German, he adjusted and improved the construction process to reduce cost. He cast shell components on sand mounds for the lifeguard rescue tower at Binz, East Germany. For the lifeguard rescue towers (1975 and 1981), sections of the shell were cast in sand moulded form work. The shell halves were then positioned together on location and mounted on the main columnar support. The later 1981 shell had thinner walls as he used a special ferrocemento with a hexagonal mesh. To achieve an optically slimmer looking shell, concrete was also sprayed (Lämmler, R., & Wagner, M., 2010).

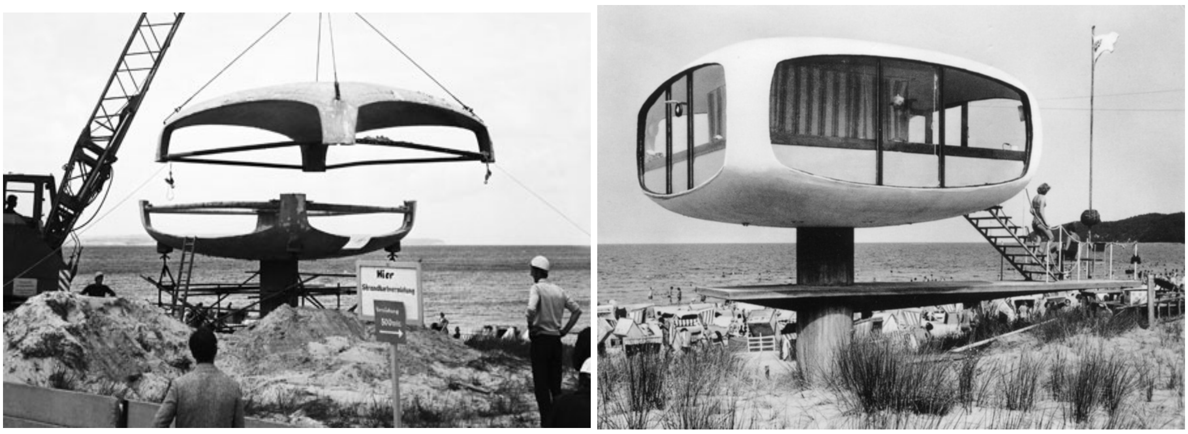


Fig 3.38 The water rescue station seems as a spaceship which is landed on the beach of Binz, on the Baltic Sea island of Rügen.(© Müther archive)

Muther's other projects - Babe book kiosk (1971) and Kurmuschel concert shell (1987) in Sassnitz were also cast in sections and assembled together.

3.3.11 Basento Viaduct by Sergio Musmeci (1975)

For the Bridge over the Basento River, Musmeci based the structure on the application of the physical models of minimal surfaces. The bridge was constructed from concrete and form-found by reiterative stages oscillating between form-finding (both physical and mathematical) and structural analysis. The form-finding process solely informed the shape and form of the completed project as concrete was poured into conventional timber shuttering. (Magrone, P., Tomasello, G., Adriaenssens, S., Gabriele, S., & Varano, 2016) Figures 3.39 describe the use of a neoprene scaled model to form-find the shell. Large scaled models were employed to understand the structure better as well.

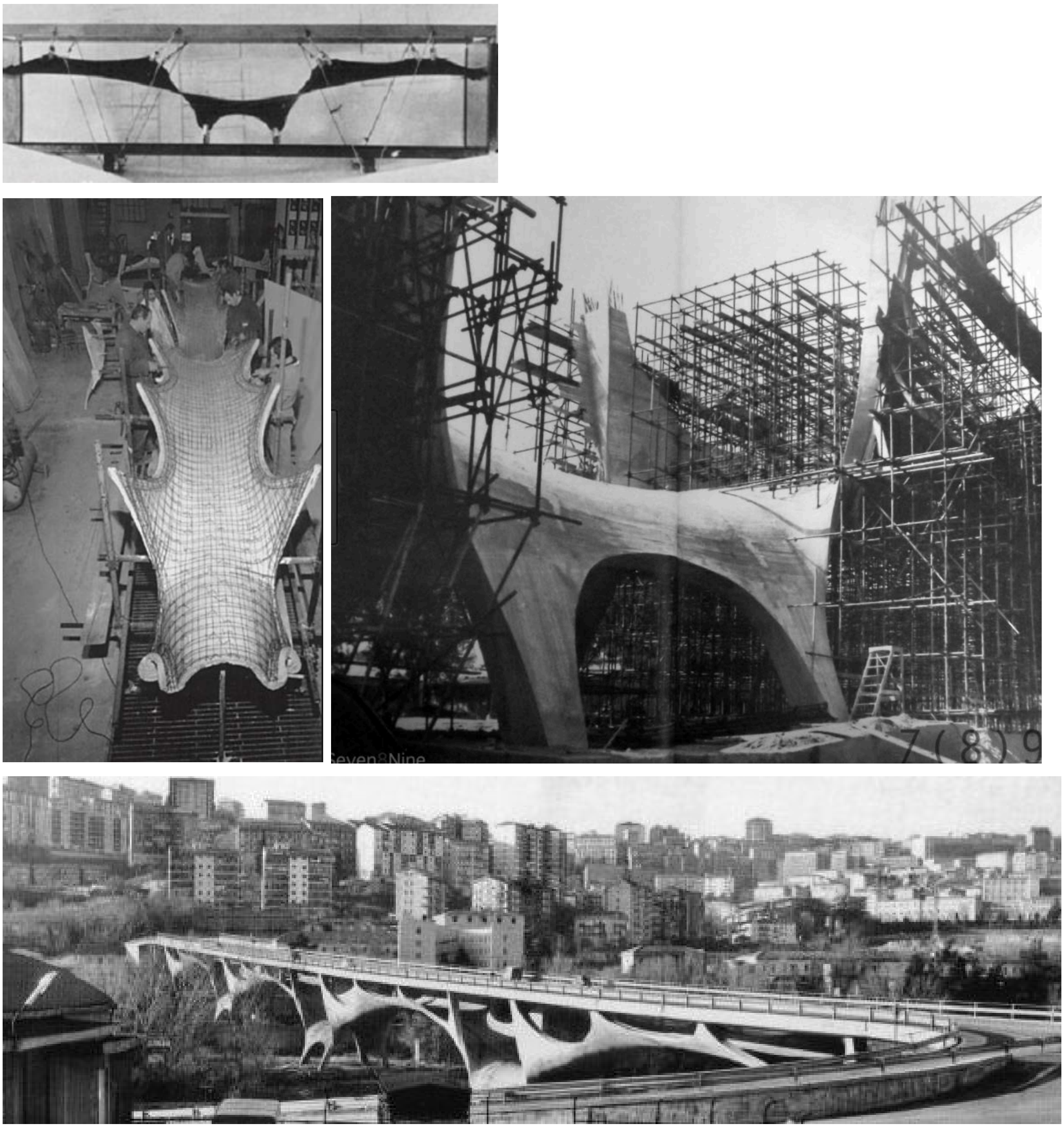


Fig 3.39 Basento Viaduct: Neoprene Model and eventual concrete model (Curti, G., Polimeni, B., & Raschi, S., 2011).

3.3.12 Form-finding's discrepancy from the building process

During the design of Basento viaduct, Musmeci focused his attention on structural stability and postponed the construction problems to a later moment. (Curti, G., Polimeni, B., & Raschi, S., 2011). This statement highlights the sometimes disparate stages of form design (geometry and structure), then construction design (formwork and casting). Isler's construction was also separate from form-finding. Isler used hanging membranes to form-find shell shapes acting in pure compression when inverted. After successful form-finding, these geometries were transferred and made into timber beams to create doubly-curved curved formwork frames. Compared to Candela's use of straight planks, this method of form-finding (although efficient and effective), unfortunately did not fully engage with construction issues to the highest sophistication. The discrepancy between form-finding and construction also suggests a design method deemed less coherent, and hence less intuitive, to the construction process of James Waller and his Ctesiphon shells (chapter 3.6.1.2). Waller's work spoke clearly of the relationship between force, form and construction. This raises the question whether this form-finding method could better relate to the construction of the shells, which is what the thesis proposal attempts to address.

Apposite to this notion is demonstrated in the works of Luigi Nervi and Felix Candela who managed to combine the two processes which resulted in a new tectonic language. They were able to do traditional concrete casting by the rapid pre-casting repetitive units. Although not wholly intended as a solution to make producing doubly curved formwork easy, Candela's use of straight planks popularised hy-pars as a possible shell design option and influenced the way he designed. Therefore, addressing construction issues at the outset may be conducive to innovations of design and construction.

Tantalisingly, the answer to reviving concrete shells may lie in finding a method of constructing concrete shells that integrated form-finding and constructional thinking better to address the issues of re-usability, re-configurability with design intuition (by ease of use and inducing a structural understanding) of the designer.

3.3.13 Factors affecting popularity of Concrete Shells

With these seminal examples used by the leading lights of shell design, thin concrete shells continued to be built and developed at an international level. However, we observe that concrete shells are less frequently built. To verify the use of gridshells as formwork, it is important to understand why they rose and fell in popularity.

Bechthold (2008) posits that the history of rigid shell structures as occurring in two phases: the first from 1912 to 1939 and the second period from 1940 to 1960s. As wide-spanning, uninterrupted spaces became the norm, a demand for clear spanning congregational spaces of worship (churches), education (schools), exposition/ convention trade centres, entertainment and sport facilities after the war had to be met.

The demand for clear spanning buildings saw concrete shells being built. Impressive examples of shell buildings included the Salone Agnelli, Torino and The Palazetto dello Sport by Luigi Nervi (1960), the Centre of New Industries and Technologies (CNIT 1958), Paris by Nicholas Esquillian - an equilateral triangular planned exposition hall with spans of 218m that made use of pre-cast concrete. The CNIT covered an area of 22,500 sqm with a clearance height of 46.30m (www.Structurae.net/structures/cnit). Also, The Hershey Arena by Anton Tedesko, the Zarzuela Hippodromo and the Recoletos de Fronteros in Madrid by Eduardo Torroja - all demanded clear-spanning spaces to be built quickly.

Concrete shells met this demand readily. Along with development in construction methods and engineering technologies, strengthened by rapid digital processing, together with relative low-labour cost saw concrete shells quickly becoming an architectural typology of choice used during that period. The economic conditions after the war played a major role too. The low cost of concrete and labour led to Nervi's invention of *ferrocemento* that combined pre-cast and cast-in-place concrete to be built cheaply and rapidly. The war itself created building programmes that called for large clear spanning but open-air shelters such as the aircraft hangars in Orvieto (1935-1942), making concrete structures popular, cost-effective and fast to build.

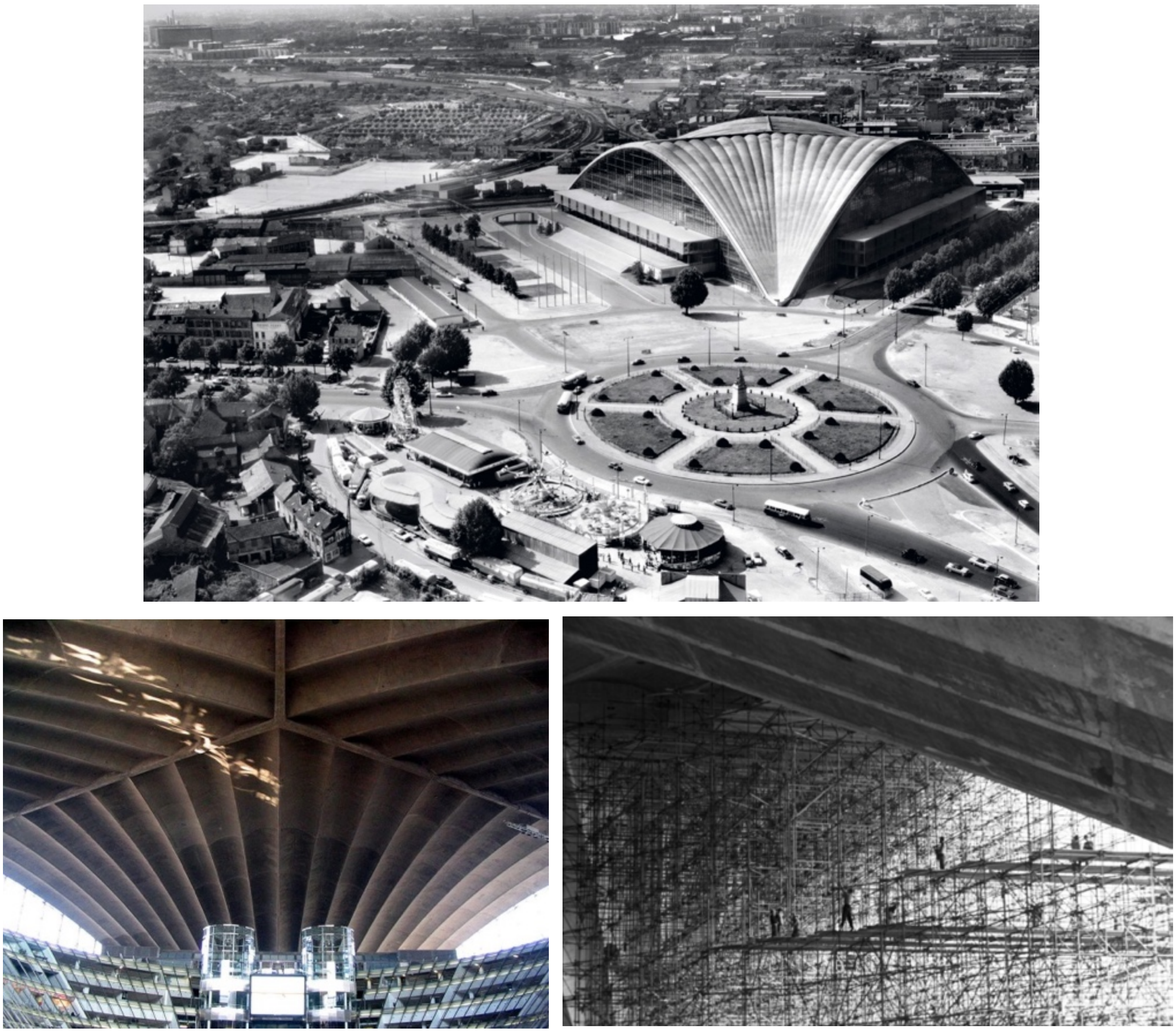


Fig 3.40 CNIT by Esquillan in Paris completed in 1958 were built with innovative double shell with internal ribs.

After the war, concrete shells in organic forms signified positivity and hope. By their expressive curves, they captured the promise and optimism. It was an exciting period where building designs became more expressive. Concrete shells was the ideal form that embodied this spirit. Free-form concrete buildings of the 50s and 60s such as TWA terminal in New York (although not proper shells) along with other curvaceous concrete structures designed by Eero Saarinen in The United States. (Boothby, T.; Parfitt, M. Kevin; R, and Charlene K, 2005) represented this attitude.

Organic forms, shells and the curve were now *à la mode*. The post-war period was an age of exciting space travel with the moon-landing of Apollo spaceship and atomic discoveries, impacting on aesthetics tastes and aspirations of the decade. The curves of concrete shells captured the spirit of this period, rebelling against the straight-line and rectilinear spaces of prevailing architectural taste.

3.3.14 Thinness and Material Economy

Efficient shells carry load primarily through membrane forces (Isler, 1994). The absence of large bending moments keep stresses low and reduces material demand. The possibility of becoming thin is derived from the most efficient force path within the shell. A shell’s structural performance is therefore dictated by form and geometry and/or curvature. (Hawkins, W. J., et al, 2016).

3.4 The Fall of Concrete Shells:

Unfortunately, concrete shells failed to be considered an attractive architectural option although they can be efficient and beautiful structures. The decline of concrete shell building is found to be due to following reasons:

1. The passing of the great shell masters
2. Changes in architectural fashion
3. Cost of labour in some countries
4. Very complex and expensive formwork
5. Limitation in flexibility of concrete shells
6. “Impractical” morphology of shells.
7. Complex Analysis
8. Material Opacity
9. Limited Building Codes/ Guidance
10. Competition from other materials

3.4.1 The passing of the great shell masters

Concrete shell activity died down as the number of shells declined from the late 70s. During a 2005 interview with Matthys Levy of Wiedlinger Associates and Khaled Shawwaf of DYWIDAG Systems US, it was observed that their offices had not been involved in any thin concrete shell project since the 1970s (Meyer and Sheer, 2005).

The passing away of the shell design masters eclipsed the death of concrete/ masonry shell building activity. This loss of shell popularity and an increasing ill-perception of concrete shells affected Felix

Candela badly. The situation destroyed his career, rendered him helpless at the latter part of his life (Cassinello, Schlaich and Torroja 2010). This sentiment was reflected in a brutally open and honest quote from Felix Candela during a lecture at The Universidad Nacional Autonoma de Mexico (UNAM) in 1969:

> *"As a matter of fact, I am as lost and disorientated as you are. I am around 60 years old and 20 of them I spent as contractor and designer of structures, I know the trade of the traditional architect reasonably well and I neither find market nor use for some capabilities that cost me so much to achieve. I am out of place in today's world and I do not know what to do nor if I am worth anything."*

An autopsy of the death of concrete shell suggested several causes – firstly, the state of shell technology, formwork, and construction methods were in direct competition with other structural technologies such as membrane technologies and lightweight steel and glass alternatives. Secondly, the social and economic outlook of the time needed to be assessed as well. Cassinello, et al (2010) reasoned why concrete shells lost favour in the architecture world of today:

3.4.2 Changes in architectural taste and fashion

Primarily, to design and apply shells in architecture, designers will not just be concerned with structural efficiencies, but also its aesthetic value. The fashion and changes in styles and perception of beauty (aesthetics) has affected architecture over time - most distinctly in the periods of Baroque, Regency, Rococo, Greek and Classical revivals. The same fashion that gave rise to popularity has also caused its demise. Similarly, after the swinging 60's, architectural fashion saw the return of the Cartesian geometry, platonic volumes and the straight line. Together with factors like construction costs, concrete shells went "out of fashion" once again, to become "a fad" (Bradshaw, et al 2002) that failed to made a comeback until in the last decade. Concrete shells was both beneficiary and victim of the capricious nature of architectural fashion, a reality which affected architectural tastes and trends of the time, inherently embedding societal values, economic concerns and political perspectives.

3.4.3 Cost of labour in some countries

Typically, concrete shells are costly due to specialist labour and falsework. After the Great Depression and the two World Wars, with labour cheap, shell construction was cost-effective. With rapid post-war industrialisation, came rising labour cost. Compared with other systems such as steel and membrane systems, even in industrialising countries, concrete shells could no longer be sustained economically.

3.4.4 Very complex and expensive formwork

Formwork and costs became the primary shortcoming, causing concrete shells to fall from favour. This remained the case despite casting innovations such as pneumatic formwork or the repetitive straight planks or modular bays. The complex formwork, seen in the construction of free-form inverted membrane shells of Heinz Isler, consisting of individually crafted beam profiles, as used in the

Grotzingen Performance shell of 1977 (Chilton, 2000). With glulam formwork costly to make, and a complicated construction process, formworks like these scored low on economics counts. If it was not for Isler's long-standing collaboration with contractors to re-use them in multiple projects, his shells would have easily lost out to competing structural systems.

Fig 3.41 Precise glulam timber formwork used to form concrete shells of Heinz Isler (copyright Isler Archives)

3.4.5 Limitation in flexibility of concrete shells

Specialist skills, complicated formwork/ erection planning, coupled with a considerable lack of flexibility of the final shell caused concrete shells to lose their appeal. Compared to other building systems, concrete shells are difficult to be adapted, extended or even make changes during or after construction such as to extend spaces on plan.

3.4.6 "Impractical" morphology of shells.

On a practical level, the morphology of shells was not space efficient in planning terms when compared to other systems available at that time. It resulted in numerous unusable residual spaces such as awkward junctions between walls and roof, making space usage difficult. These impracticalities were evident in the experimental work of the Ball Houses series of Heinz Isler and specifically the difficulties in furniture placement within the completed Balz House (Chilton, 2000). This resulted in the need for bespoke shuttering of formwork. The Bini shells and Monolith concrete domes (Chapter 4) cast from pneumatic formwork suffer from not being able to be adaptable for changes to the building at a stage during or following the construction process.

3.4.7 Complex Analysis

Candela was inspired by Maillart's approach of simplified mathematical calculations, as opposed to rigorous analysis, which Candela found "delightfully sympathetic and encouraging." (Garlock and Billington, 2008). This application of elastic analysis to concrete has been a perennial concern of Nervi and Candela. Shells were difficult to analyse. Before the advancement and use of sophisticated computer software, shells were analysed using complex mathematics such as manual 4th order partial differential equations. This was not only tedious, but gave complicated calculation results difficult to understand and interpret, making the process expensive. Nowadays, powerful analytical software programmes are commonplace to ensure shell forces are verified. Arups has developed the software Oasys GSA that considered material property in non-linear analysis of concrete shell structures. Some of the early examples, such as Cottbus Aircraft hangar in Germany suffered concrete creep which led to the catastrophic collapse drove home this shortcoming (Hines and Billington, 2004).

3.4.8 Material Opacity

The optical opacity of concrete also undermined the form-giving potential of concrete. Although concrete shell surfaces can be punctured through to allow light penetration, this had led to further complications to what is already complex structural analysis. Michael Flynn of the Pei Partnership observed that although shells are still being designed in their office, they are not in concrete, but in steel and glass (Meyer and Sheer 2005) due to their material quality, most importantly its transparency. However, light penetration was applied to great effect by Candela in many of this concrete shells in Mexico City by placing repeated shells with glazed areas between to enable light to flood into the space beneath.

3.4.9 Limited Building Codes/ Guidance on environmental performance

Shells are not compatible with modern environmental standards. Many examples of thin concrete shells were either built as outdoor shelters (hangars and outdoor garden pavilions) or in warm climates like in Mexico where Candela's shells flourished. The redundancy of thermal insulation allowed shells to become thin. This expression of thinness calls for a new way of detailing a solution to climatic problem as insulated concrete shells.

Heinz Isler's shells in temperate Switzerland incorporated insulation within shell build up but to express this thinness, he designed tapered and upturned edge details which also provided additional edge stiffness. In the Wyss garden centre shell (1962), trussed formwork made from glulam timbers were used. Over this, Isler laid thin timber boards placed at regular intervals across the trusses and over this, wood-wool slab insulation was placed and acted as permanent shuttering (Chilton, 2000). This was stiff enough to support worker's weight but be flexible enough to bend into the curvatures before reinforcement bars were attached above and concrete applied. When the supports are removed, the thermally insulated surface is also acoustically insulated. This structural expression could easily become inelegant if the designer lacked aesthetic awareness and allowed the shell to have a uniform thickness throughout. This aesthetic consciousness coupled with structural understanding also inspired Torroja to taper the thickness of the Zarzuela shell to express the illusion of shell thinness at the edges.

3.4.10 Competition from other materials

Monolithic concrete shells fought a losing battle against newer and brighter lightweight steel, cable nets, and membrane roof structures in the age of the High-Tech movement. The exposed structural frame represented the architecture of filigree, component design and visual transparency. A new preference for large span glazed roofs could be created from glass systems rather than opaque concrete as roof coverings. Also the demand for large-span retractable roofs for stadia design also rendered concrete shells archaic (Meyer and Sheer, 2005).

3.4.11 Environmental use

In the past, concrete was a material associated with less desirable environmental qualities - high embodied energy of cement production and high use of water. These factors contributed to their fall in popularity. However, through the contemporary works of SANAA and Toyo Ito in the last 10 years, there now seems to be a resurgence of popularity of concrete shells. They are now valued for their thermal mass - the ability to absorb, store and release heat. Exposed concrete has re-establishing itself as a material of environmental value. Exposed to the internal environment, the large internal surfaces with their thermal mass readily act as a heat retainer to release heat into the internal space. Due to their curved surfaces, concrete shells also help to distribute heat through conduction and induce convection currents within the interior environment. Concrete shells could also be useful in producing acoustic and illumination.

3.5 Discussion of concrete thickness:

Concrete shells are concerned with form and space created. The quest for thinness with increased structural efficiency is also improved with computational analysis and digital fabrication methods.

Table 3.1 below shows shells gaining wider spans over the last nine decades with the widest concrete shell dimensioning 218m at the 1958 CNIT by Nicholas Esquillan. This was achieved by careful structural design of 3m deep diaphragm walls to be elaborated in chapter 3.6.1.4. The table also shows that physical model as a form-finding tool increasingly replaced by digital form-finding processes as computerised softwares become more powerful in shortening design times.

Table 3.1 compares the dimensions of seminal concrete shells designed in the 20th Century. An unexpected observation is that although shell spans have increased, shell thickness has thickened disproportionately. The Teshima Art Museum (2010) concrete shell registered a shell thickness of 250mm/ 41.2m span (0.6 % ratio) compared to the 15mm/ 12m span (0.1%) achieved at the Cosmic Ray Pavilion (1951). Even with technological advances, the 2010 shell seemed to have become 6 times thicker than its Mexican predecessor built almost 60 years ago!

This suggests digital technology and new shell analysis allowed almost any shapes to be possible, even at the expense of shell thickness (i.e. material economy) to create improper shells (with large bending moments). Reinforcement meshes are becoming less of a precautionary measure in concrete shells (as collapse prevention or to realise tight curvatures), but perform as primary hidden structural elements to alleviate bending moments. Recent shells are thickened, heavily steel reinforced (Rolex Centre (2010) and the Grin Grin Park (2006). Conversely and interestingly, it was the lack of advance digital analysis that kept shell forms simpler and with purer on structural terms (proper shells in pure compression).

project	Year complete	designer	formfinding	formwork	span	rise	thickness	Reinforcement details (if known)
Jena Planetarium	1922	Frank Dischinger	Mathematical	Metal geodesic dome	25m	12.5m	60mm	Wire mesh sacrificial
Leipzig Market Hall	1929	Hubbert Ritter (architect) Frank Dischinger And Dywidag	Mathematical And a 1/6 scale model	Zeiss-Dywidag method Gunnite on steelbar framework	65.8m (roof)	-	90mm	-
Zarzazuela Hippodrome Madrid	1935	Eduardo Torroja	Paper model and Mathematical	Timber boards	13m	-	50mm	Tensile steel reinforcement
Fronton Recoletes Madrid	1935	Eduardo Torroja	Physical Model, mathematical analysis	Timber boards	32m wide 55m long	-	80mm thick but at intersections 150mm	-
Cosmic Ray Pavilion	1951	Candela	mathematical	Timber boards supported by scaffolding	12m	5.5m	15mm	Steel 1/8 inch diameter wire placed 4 inches
Xochimilco Los Mantiales	1958	Candela	mathematical	Timber boards supported by scaffolding	42.4m roof 32.4m supports	5.85m centre	40mm	Stiffening Steel at groin
CNIT	1958	Nicolas Esquillan	Mathematical	Timber boards	218m	46.3m	65mm set 3m apart	Steel rods
Bubble Shells	1964 onwards	Heinz Isler	Physical Model, mathematical analysis	Timber boards	22m x 22m 54.5m	varies	varies	-
Sicili Shell	1969	Heinz Isler	Physical Model, mathematical analysis	Insulation supported on timber beams	58m	8.75m	100mm	mesh
Grin Grin Park (consists of 3 shells)	2005	Toyo Ito/ M Sasaki	digital	Timber boards	70m	5m	40mm	Mesh reinforcement
Kakamigahara Crematorium	2006	Toyo Ito/ M Sasaki	digital	Plywood tabled section blocks at 1m intervals	70m	60m	200mm	mesh
Rolex Learning Centre	2010	SANAA/ M Sasaki	digital	Timber tables	80m	varies	between 400mm and800mm	Steel rods normal diameter 19mm Hollow slabs
Duxford Aircraft Museum	1997	Foster and Partners	digital	Pre-cast concrete panels	90m	Min 16m	-	Rebars and precast concrete panel
Teshima Art Museum	2010	SANAA/ M Sasaki	Digital	Earthmound	43m	5.12	250mm	Mesh reinforcement

Table 3.1: Statistics of key concrete shells designed and built in the 20th Century showing the span, rise and relative shell thickness adapted from Sasaki (in Adriaenssens, 2014).

Therefore, it may be inferred that the advancement of structural analysis, has taken away the purity of structural functions of shells. In other words the advent of digital technology has unlocked shell possibilities, however at the expense of structural rationale. This view was shared by Sasaki, 2014 who said of the TWA Flight Centre (as pseudo-shell i.e. not completely structurally rational, the shell was a form-active free reinforced concrete shell) suggested that "a way to break through the barriers imposed by engineering and geometry restriction, which tended to reduce the visual potential of shells. Compression -only (i.e. proper shells) is still the main concern for contemporary shells, but flexible designs that allow tension and bending stresses to some degree are needed. Modern shells need to take full advantage of today's design environment and balance engineering knowledge with visual expression." (Sasaki in Adriaenssens et al 2014)

3.6 **Concrete Shell Formwork**

> *"The formwork is the actual architecture, and the concrete is only there to document it in order to permanently preserve its memory, just as a death mask is made to preserve the facial features of a departed person."*
>
> *Windeck, 2016* (about formwork for Kakamigahara Crematorium Roof 2006).

A critical assessment of formwork technologies

Numerous technologies have been developed with the purpose to construct concrete shells in the last decades. Formwork can be divided into two main types, rigid types (including timber, earth mound and pre-cast elements) and those which are soft and flexible. The figure below represents the various methods available. Rigid formworks will be discussed in this chapter whilst soft and flexible formwork will be discussed under fabric formworks as a second constituent technology in Chapter 4.

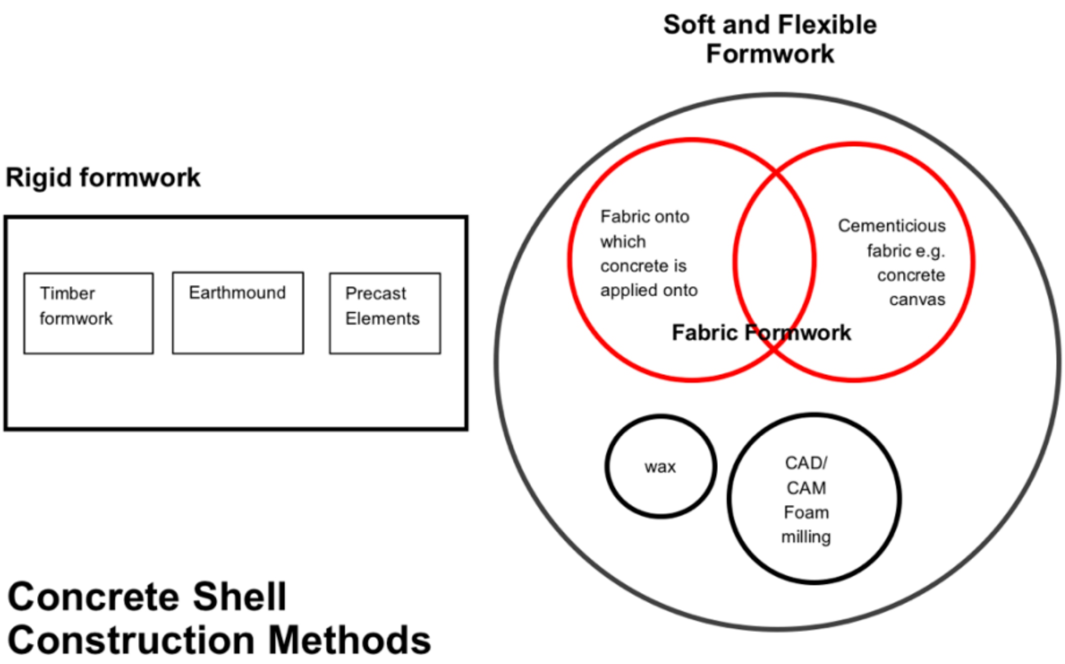


Fig 3.42 The classification of concrete shell construction method: rigid vs soft and flexible formwork

3.6.1 RIGID FORMWORK SYSTEM:

Timber formwork

The traditional formwork to shape concrete shells used rigid timber planks arranged to produce curved shapes/ supports. Timber formwork was suitable and effective in supporting the weight of the construction workers as well as shoring concrete (Bechthold, 2008). The first concrete shells by Dischinger at Jena in 1922 (Chapter 3.3.2) used timber as a backing to prevent concrete from falling behind the shell (Addis, 2007: p 483) in a system known as “tokret”.

The appearance of concrete shells borrows the imprints of timber planks used. These timber marks were something which Candela valued and retained to express the process of formation from straight planks (Lee and Garlock, 2009).

Fig 3.43 The formwork of Candela supported by timber scaffolding support underneath was strong enough to allow working access and also the intense amount of reinforcement applied. This was a very dangerous form of construction by today's standards. http://www.columbia.edu/cu/wallach/exhibitions/Felix-Candela.html

3.6.1.1 Candela's timber planks

The method of using straight elements to create curved surfaces influenced the way Candela designed with ruled geometry. Ruled geometries are curved surfaces that are formed of straight lines. These are manifested through forms such as hyperbolic parabolas or hy-par (of which Candela used extensively), conoids, hyperboloids, cylinders and cones. Candela was keenly aware that ruled geometries also meant loading could be calculated and analysed (Faber and Candela 1963: p30-32). Very importantly, by using ruled surfaces, Candela was able to simplify formwork as these doubly-curved shells could be formed from straight boards, which were reusable, making them economical. For Candela’s umbrella structures, the falsework was reused several times on a project. For example, for Rio’s Warehouse he concreted four umbrellas so that one week later he could decentre the forms and concrete another set of four (Garlock and Billington, 2008).

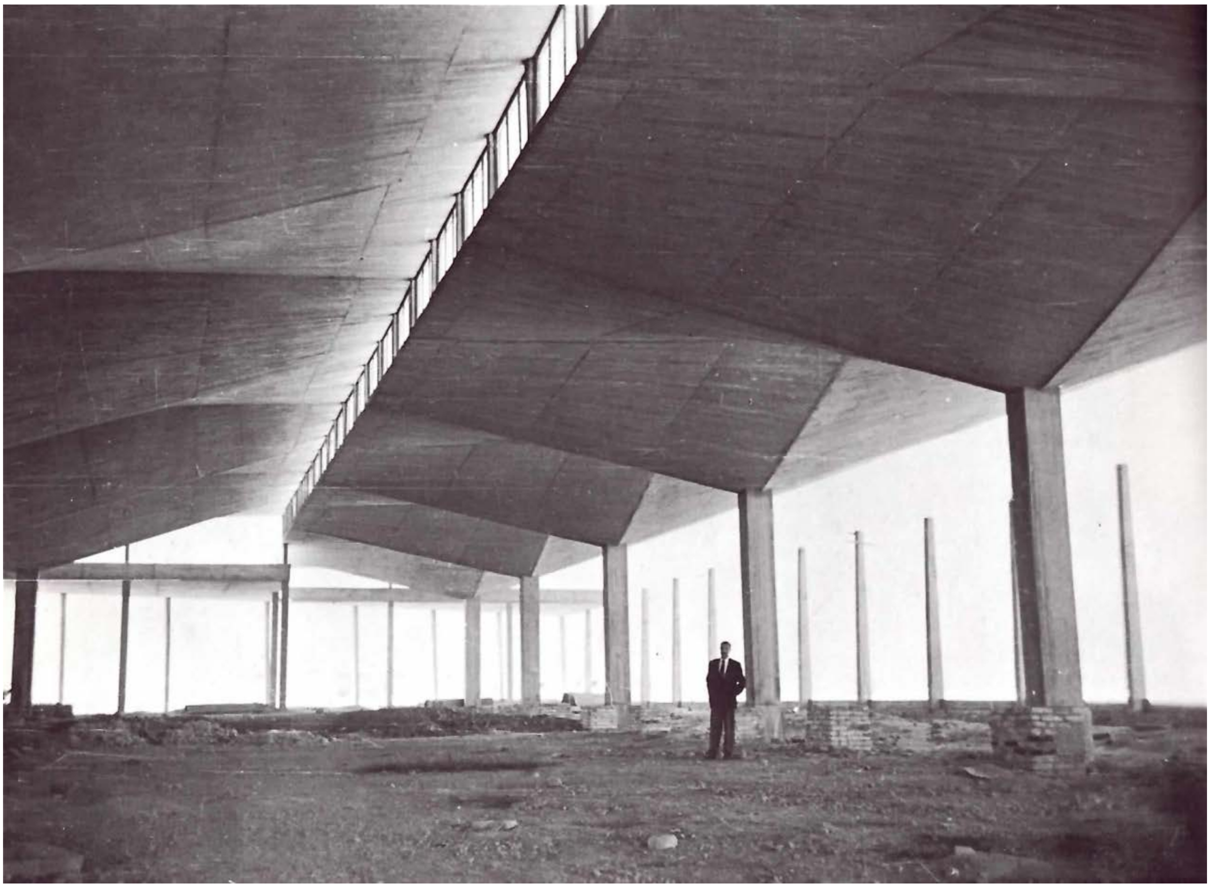


Fig 3.44 Felix Candela standing beneath one of the ‘umbrellas’ during construction, Rio’s Warehouse, Insurgentes Norte, Lindavista, Mexico City 1954 Four of these umbrella shells were cast from the same set of timber formworks.

These shapes opened up form possibilities for designers. The complexity of design could now be managed by varying and repeating the ubiquitous hy-par form. The fact that Candela was developing a signature way of designing and constructing saw his shell forms respond to computational/ analytical limitations at that time. These designs and concrete shell forms were hence guided by what available technology could do at that time, and to great aesthetical success.

Felix Candela, Luigi Nervi and other prolific shell builders could build because they were both designer and builder. As contractors, they were conscious and keenly aware of real commercial applications and issues of speed, ease and cost. Being both contractors and designers also meant that they were able to very often build untested ideas, as a way of managing risk and conventionality.

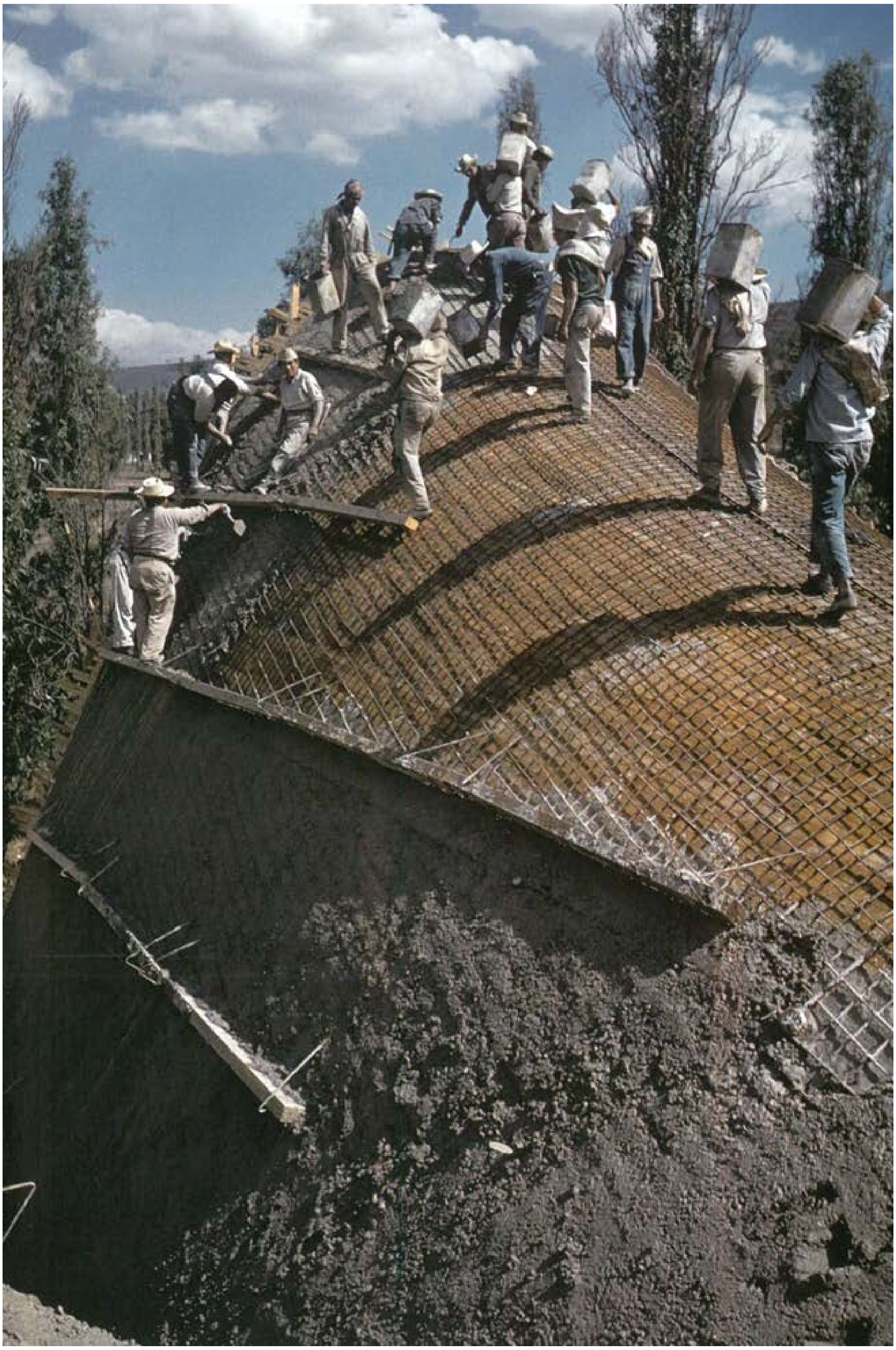


Fig 3.45 The very complex and intensive labour of hand trowelling Felix Candela's shells in Mexico.
http://castingconcrete.wordpress.com/2012/01/ http://kbreedlove.wordpress.com/2011/02/04/thin-shell/#jp-carousel-1

Fig3.46 The very complex and intensive labour of hand trowelling Felix Candela's shells in Mexico.
http://castingconcrete.wordpress.com/2012/01/ http://kbreedlove.wordpress.com/2011/02/04/thin-shell/#jp-carousel-1

Again, historic photographs of Candela's shell construction depicted complex scaffolding-intensive method of building where dense "forests" of timber scaffolding were used. As the decades saw concrete shells gaining popularity in Mexico where labour and building material was cheap, one wonders how shells constructed this way would perform in a different economic climate such as in Isler's Switzerland. (Switzerland was approximately five times richer than Mexico. The GDP per capita figure for Mexico at 1960: US$342 (Mexico) and US1787.40 (Switzerland)). External social, economic factors such as the low labour cost in Mexico provided fertile testing ground to facilitate the public's acceptance of Candela's shell ideas.

3.6.1.2 James Waller

In 1955, James Waller patented a method of constructing concrete shells by allowing fabric to act as formwork upon which concrete was applied manually or eventually by gunniting (Veenendaal et al, 2010). Using this method, he was able to construct shells of spans up to 150m. The system relied on fabric being draped to form stiffening corrugations between pre-fabricated and reusable rigid arches that conformed to funicular curves. This method importantly allowed Waller to eliminate the complicated use of metal mesh reinforcements deemed complicated and difficult to construct (Waller 1953). However, the disappearance of this method was associated with the fall of concrete shell building activities, but also it was pointed out that it was likely to crack at the top of the shell (anon, 1963) and poor thermal quality was noticed (Naidu, 1963).

Fig 3.47 the method of constructing by Waller created corrugations which stiffened the double curved surfaces.
(Taken from http://cargocollective.com/ciaranconlon/Research-on-James-Waller)

3.6.1.3 Heinz Isler's glulam timber formwork

Whilst the consistently vernal climate of Mexico played a major role in enabling concrete shells to stay singly-layered and impressively thin, concrete shells in areas with harsh winter required thermal consideration. Insulation is required in the case of Heinz Isler’s shells in temperate Switzerland. These problems were solved by the use of insulation panels as permanent shuttering In the 1962 Wyss Garden Centre shell, thin timber boards were placed at regular intervals across the beams or trusses. On top, insulation were positioned and acted as permanent shuttering whereupon concrete was laid.

Fig 3.48: Rigid timber trusses were formed for the shell casting in many of Isler's works including Wyss Garden Centre (courtesy Heinz Isler Archives from Chilton, 2000).

Fig 3.49 The Bespoke glulam system used by Isler. Wyss Garden Centre, Switzerland by Heinz Isler (1961) http://upload.wikimedia.org/wikipedia/commons/0/05/Gartencenter_Wyss_Zuchwil_02_09.jpg

Isler's shells used specially-made timber formwork, precisely engineered and profiled to follow the bespoke curvatures. Having built up a standing working relationship with his long collaborating contractor, W. Bosigor, to achieve economy, he adapted his designs to reuse pre-used timber sections for new designs with similar geometries (Chilton, 2000: p 107).

Evidently, successful shell builders were effective in addressing constructional economics. To design and build shells, the system needed to address challenges of cost, amongst many other factors. It was clear that Isler was aware of building economics and tried to address these concerns.

3.6.1.4 CNIT (Centre des Nouvelles Industries et technologies), 1956-1958 Paris, Nicolas Esquillan

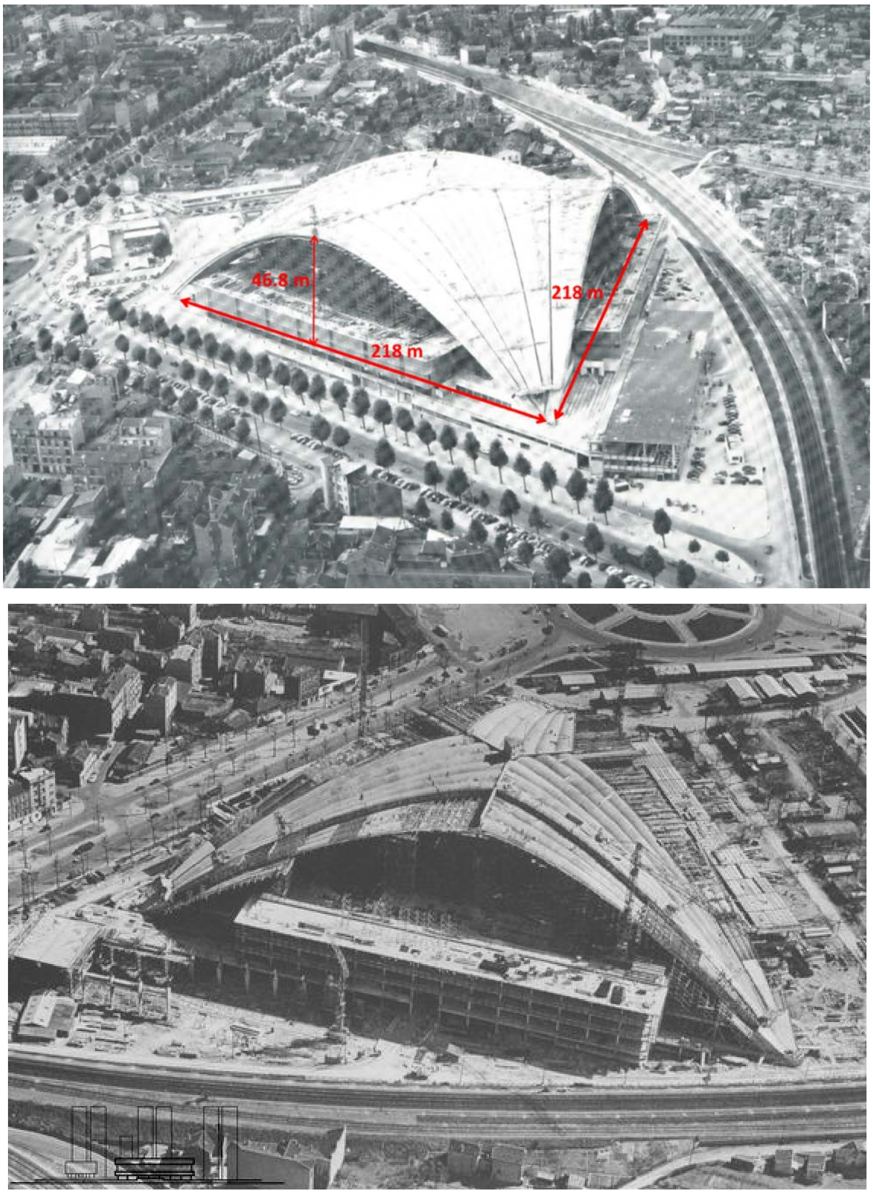
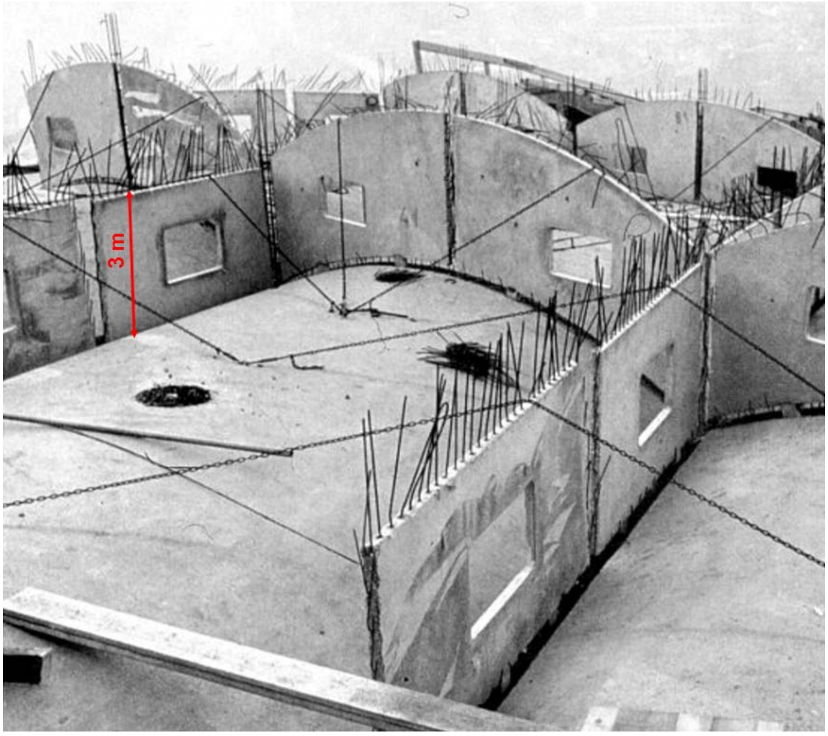


Fig 3.50 CNIT by Nicholas Esquillan, 1958 (www.vision8och13.org)

Situated at the La Defense area of Paris is one of the largest concrete shells in the world to date. Engineered by Nicholas Esquillan, it finished construction in 1958. On plan, it is a equilateral triangle

218m on three sides rising up to a height of 46.3m. The shell is a double skinned shell devised as two shells about 3 metres apart and 65mm thick. They are joined by a series of diaphragm walls to create thin wall tubes. These are formed from precast panels assembled together on site.



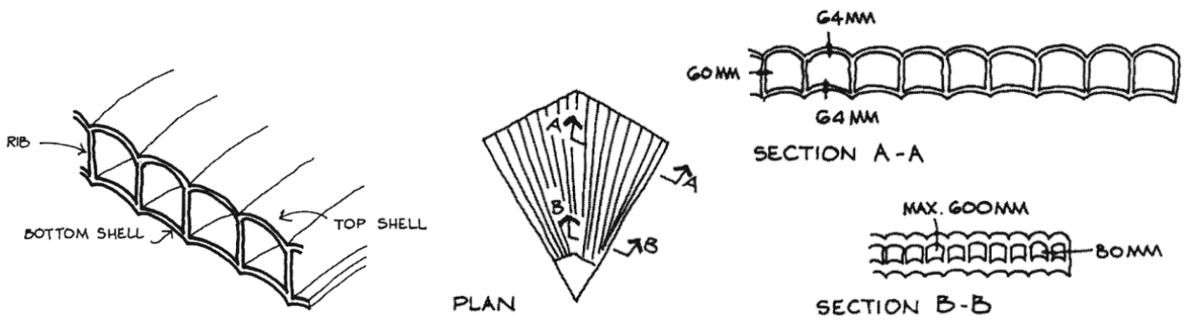


Fig 3.51. The construction of CNIT shell in two layers, the top and bottom. (copyright Millais, 2005)

3.6.1.5 Marignane Hangers, Provence, France

In 1942, two concrete shells were designed as a double hangar at the airport of Marignane in France. The two units are covered by six 101.5 m waves, 9.80 m in width and 12.10 m for the sag. They comprise a concrete shell, 6 cm in thickness, with steel reinforcement. The formwork for this series of shells was innovative as they were moving timber moulds. The formwork are on a rolling system pivoting on the rolling blocks to allow it for reuse. These pre-fabricated sections were attached on roller rails which are pushed along to create these arches pieced together and craned into position. Wire netting was also used as reinforcements. The first roof measuring 60m x 100m was constructed in 38 days (including overtime and Sundays) whilst the second hangar was constructed in 23 days. (Motro and Maurin, 2011)

Fig 3.52. The hangar consists of two sections with six coffers each.(courtesy www.culturecommunication.gouv.fr)

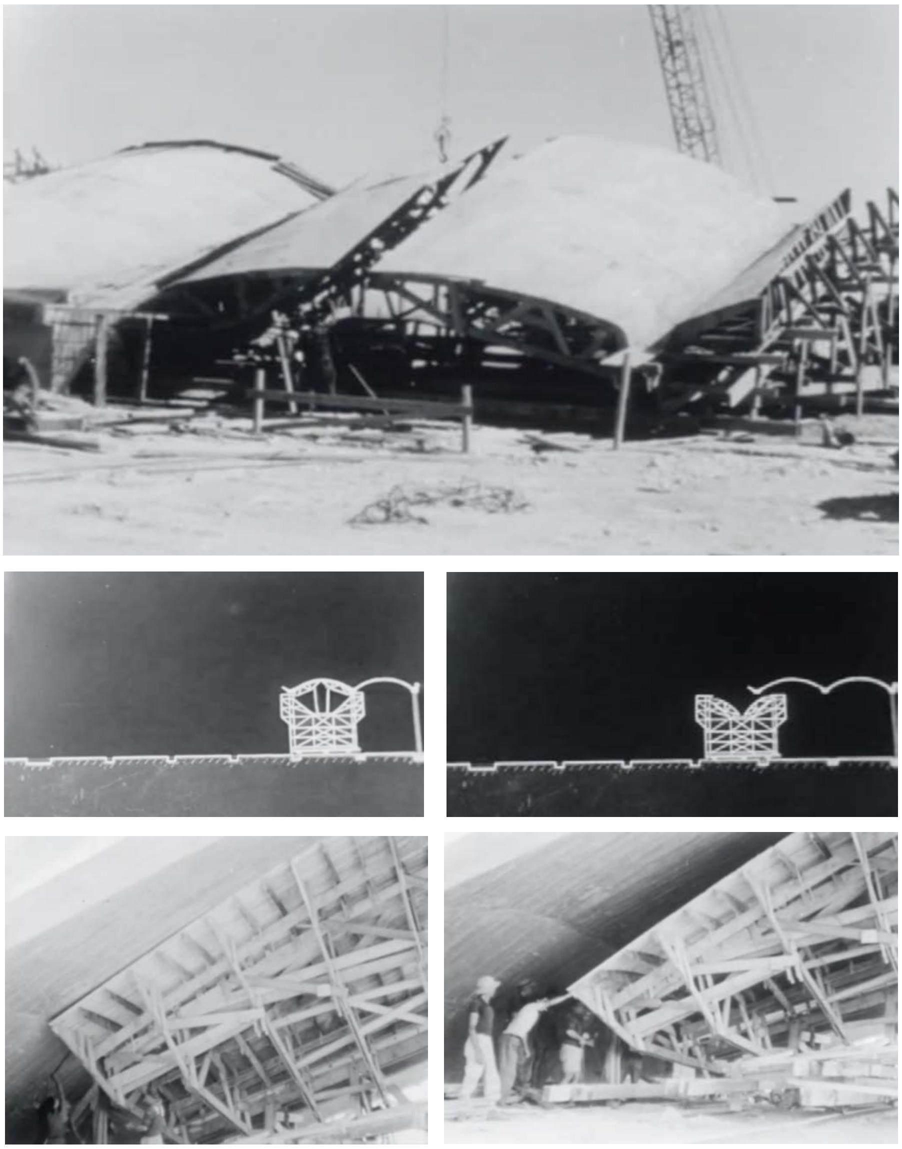


Fig 3.53 Decentring of formwork taking place at the abutments of the shell and is moved along the length of the hangars. (www.vision8och13.org)

3.6.1.6 Contemporary Timber Formwork

In recent years, with CAD/CAM advances and new materials, process efficiency and economy (material wastage) could be optimised. Completed in 2006, the roof of the Island City Central Park Grin Grin (2005) which measured 190m long, 50m wide and with a thickness of 40cm, Mutsaro Sasaki engineer form-found and designed reinforcements digitally. Contemporary manufacturing processes and cutting-edge structural analysis made use of conventional plywood formwork and steel mesh realisable. The plywood framework were constructed in three sizes- 1mx 2m, 1mx4m and 1mx1m pieces, were factory cut and site assembled. The roof formwork was then precisely joined by 400 workers before 2000 cubic metres of concrete was poured onto very dense mesh of reinforced concrete (Bechthold, 2008: p149).

Fig 3.54 Grin Grin Island City concrete shell by Toyo Ito and Mutsaro (copyright of K. Ooni)

Following on, in the structural design of the concrete roof shell for the Kakamigahara Crematorium in repeated collaboration with Toyo Ito, this project saw Mutsaro Sasaki's structural refinement. This time, the shell became thinner, now measuring 20 cm. Again, the fabricator made use of CAD-CAM technology to create special frameworks to support concrete and reinforcement meshes. Large wooden beams were placed at 1m intervals and smaller beams every 25cm. Specially shaped plywood was used in areas with increased curvature to result in a finish that was finer and smoother (Sasaki, 2010: p131-144). The tectonic expression of the shell was porcelain-like as all joints were smoothed by construction workers producing a surface that purposely disowned the formwork upon which concrete was cast, a departure from expressive tectonic celebration of timber formwork board markings of Candela’s Mexican shells.

Fig 3.55 Surface quality comparison

Top: courtesy of Addison Godel (https://www.flickr.com/photos/doctorcasino) of the concrete finish at Kakamigahara Crematorium, Toko Ito and bottom: The painted board markings of the Cayoacan Market by Felic Candela in Mexico City (1955)

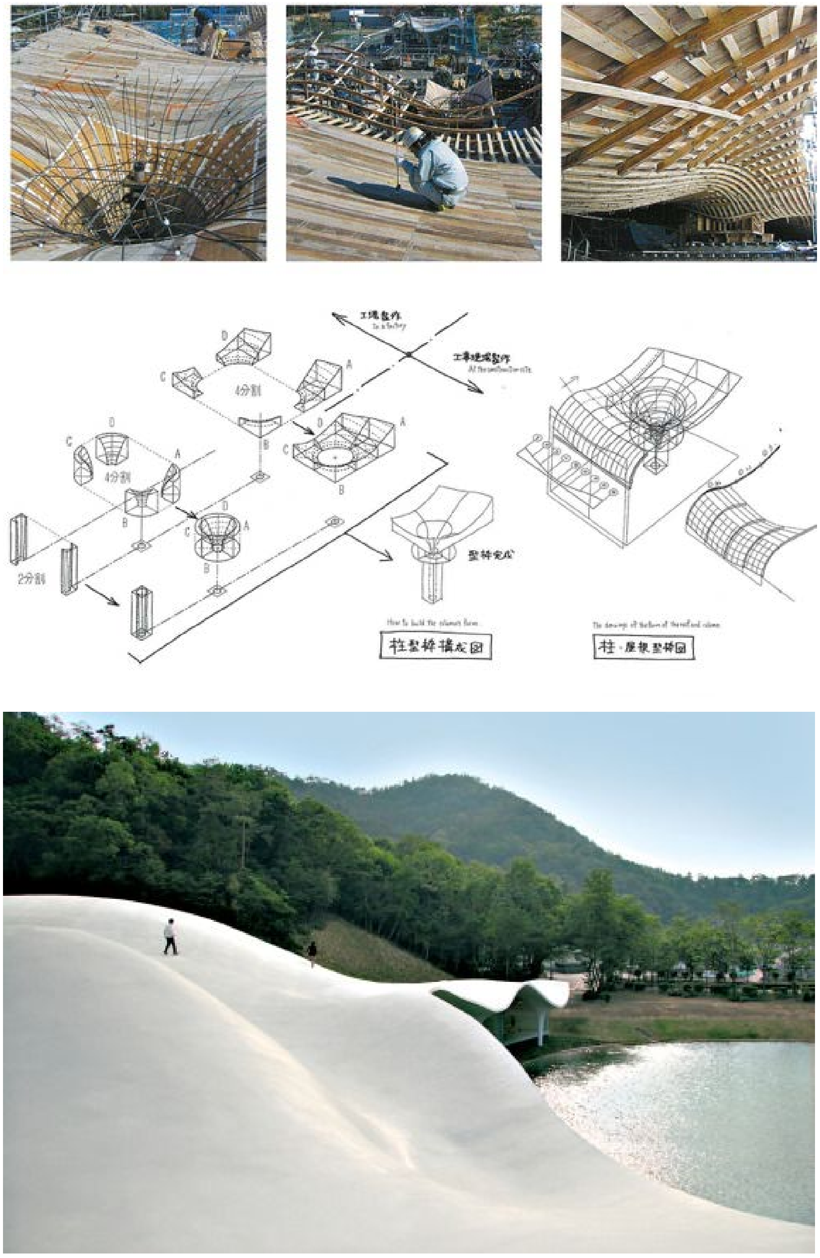


Fig 3.56 ‘Meiso no Mori’ Municipal Funeral Hall, 2004-06, Kakamigahara Japan. Concrete roof. Photos: Detail: DETAIL 2008.07-08

Contentiously, the Rolex Learning Centre by SANAA loosely recognised as a shell, the structure experience tremendous bending moments. For the construction of the walkable surface at the 2010 Rolex Centre at EPFL, a field of 1400 bespoke casting tables measuring 2.5m by 2.5m wooden casting table was used, each having a unique and precise curved geometry that formed a smooth 800 mm deep concrete slab. The architects used this continuous surface measuring 166.5m x 121.5m on plan to create an undulating indoor topography blurring the boundary between room and circulation, with complex level changes (Sasaki 2010 p131-144). In these examples, the architect sought a polished finish as seen in the figures below, somehow hinting the grid of formwork trestles that once supported the concrete.

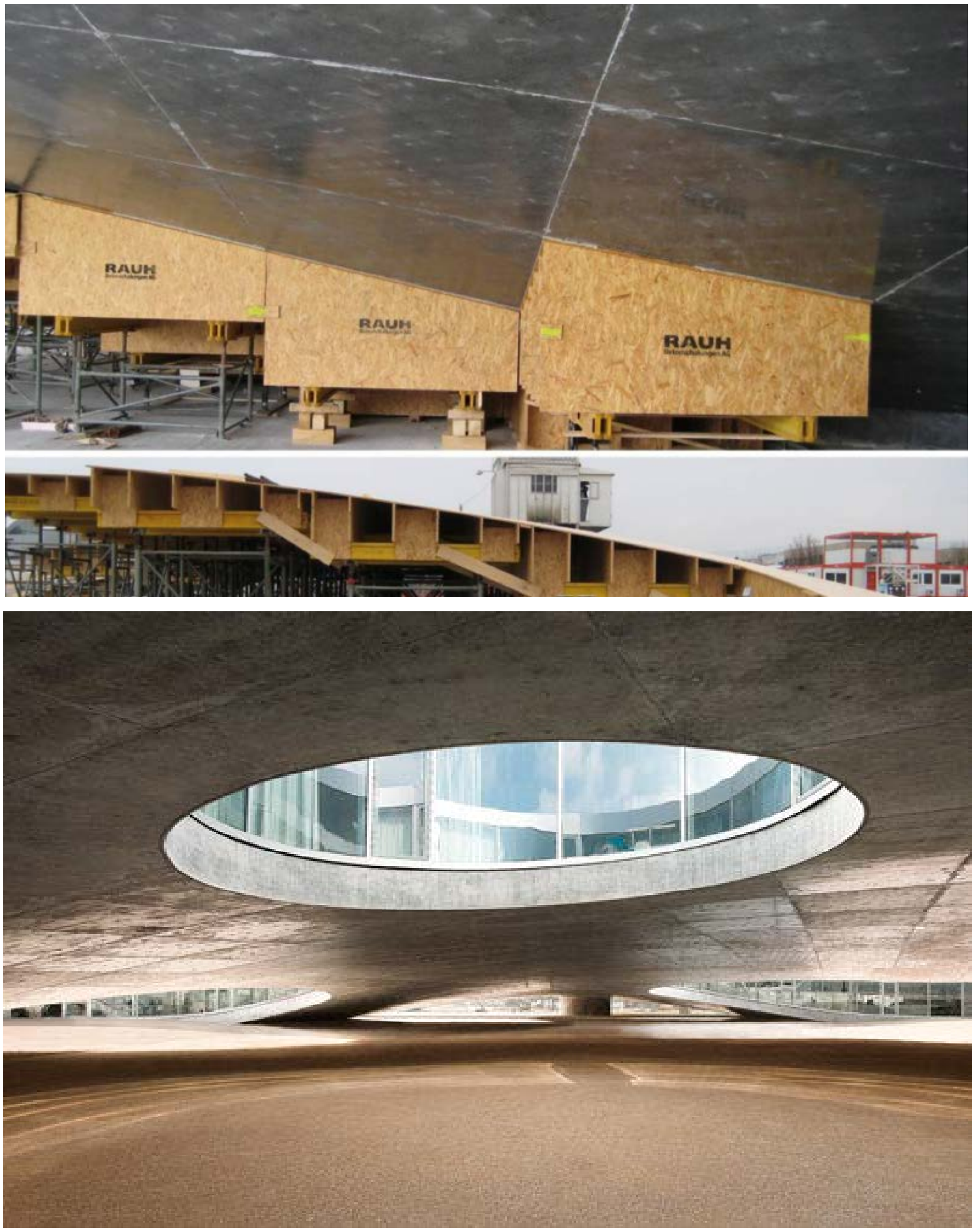


Fig 3.57 Special adjustable casting tables had to be designed and be constructed in the construction of The Rolex Centre Shell by SANAA.

It is clear that formwork is a vital element in the design of concrete shells. To achieve the original architectural vision, many of these concrete surface structures required complex and specialised formwork design, making shell structures expensive.

In these recent examples, CAD/CAM technology and digital analysis made complex timber formwork possible. Powerful form-finding software also helped remove difficulties of reinforcement designs. Complex geometries are also now possible with the help of modern timber engineering (moulded plywood), but such solutions remain difficult to justify economically (Deplazes, 2005). In other words, although the advancement of digital technology made construction of complex shapes possible, design cost and formwork cost has not made concrete shells cheaper when compared to other structural systems.

3.6.2 Pre-cast Elements

3.6.2.1 Pier Luigi Nervi

As seen earlier, the innovative use of precast panels stemmed from the need to construct rapidly and efficiently. Acutely aware of the requirements of post-war construction economics, Nervi's construction innovation responded directly to the given economic situation. A contractor working in war-time Italy (1936-1939), he designed and built eight aircraft hangars by pre-casting concrete trusses. To simplify structural analysis and to make their structural behaviour more predictable, Nervi made the hangar supports symmetrical (Billington, 1983).

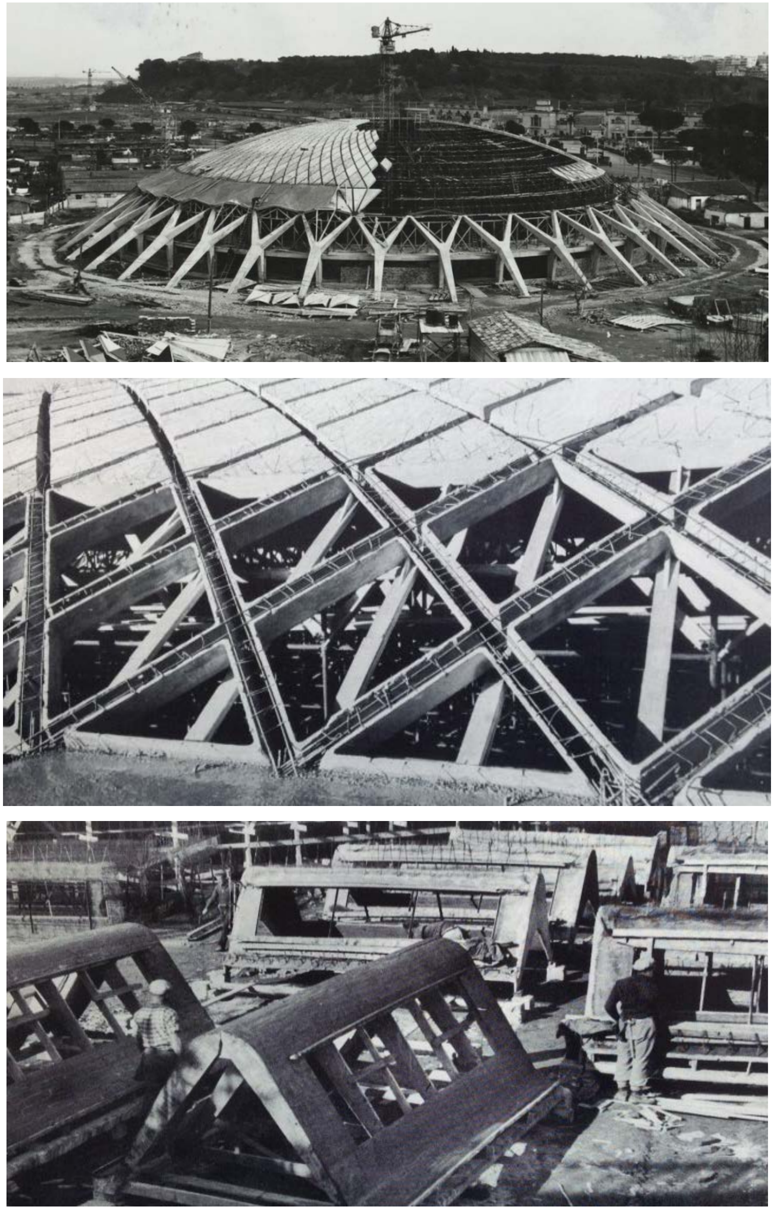


Fig 3.58 a) (top) Palazetto della Sporto in Rome. Fig 3.58b (bottom left): precast panels assembled and ready for stitching concrete by pouring concrete in the valleys between the travelloni . Fig .3.58c (bottom right) Preparation of pre-cast concrete modules at ground level at Salone Agnelli, Torino. http://robertavanali.blogspot.co.uk/2011/02/architettura-come-sfida-pier-luigi.html

Nervi's method involved concrete panels known as *travelloni,* pre-cast with *ferrocemento* on ground level first, and then raised into position. This reduced the use of vertical supports. With reinforcement bars tying them together, concrete was then poured in grooves between. What resulted was a method that not only used available materials and was fast to build, making them affordable and expressed structural rationale with constructional logic. Nervi famously said, "the process is effective from a technical and economic point of view and resulted in a great plastic richness" (Nervi 1965). His Salone Agnelli in Turin and the Olympic buildings in Rome remain strong affirmations of his ethos (Billington, 1983). Although his idea of repetition was progressive and aligned with industrial ideals of mass production, Nervi's shells, exposed this on the inside exuding attractive aesthetics. His shells were highly economical. His repeated hemispheres and barrel-vaults which encapsulated that exact spirit. Today, it is tantalising to speculate whether Nervi's structures may take on more free-forming shapes with digital technologies and analysis available.

3.6.2.2 American Duxford Aircraft Museum, 1997 by Foster and Partners

The construction of Duxford Aircraft museum by Foster and Partners made use of a hybridised way of 900 precast panels laid out in a double-layer system. This is then stitched together by pouring concrete over the top to stitch the concrete shells together (Bechthold, 2008).

Fig3.59 a) (top) exterior view of the Duxford Aircraft Museum. Fig .3.59b (bottom) Interior view of the Duxford Aircraft Museum. (copyright Foster and Partners)

Fig 3.60 Nine hundred precast concrete panels being hoisted into position before concrete is poured onto the top surface to stitch the panels together. (copyright Foster and Partners)

The controlled and repeated nature of the shells suggests an awareness of material economy and an understanding of structural logic. Today, pre-cast concrete panels are still used. Contemporary projects that applied this construction method include the above Duxford Aircraft museum (1997). Designed by Foster and Partners, 900 pieces of pre-cast concrete panels were laid out on a overlapping/ double layer system with plates placed 90cm apart. The pre-cast panels were then joined together by a concrete pour in the same way that Nervi built his shells decades before.

3.7 Other Formwork Systems Related to Concrete Shell Building

Whilst more conventional ways of creating concrete shells have been presented, other non-conventional methods have added to this repertoire since.

3.7.1 CNC-Milling Technologies

Foam formworks digitally generated and CNC-milled for reinforced concrete shells are being investigated by Prof Dombernowsky and Asbjørn Sondergaad of Aarhus School of Architecture and other researchers including Prof Arno Pronk at The University of Technology in Eindhoven, Holland. Large-scale architecture projects have benefitted from these technologies including Der Neue Zollhoff in Dusseldorf by Frank Gehry Architects (Kolarevic, 2001, p277) and CNC-milled timber moulds of the Rolex Learning Centre in Lausanne, Switzerland by SANAA (Scheurer, 2010).

3.7.2 Wax Milling

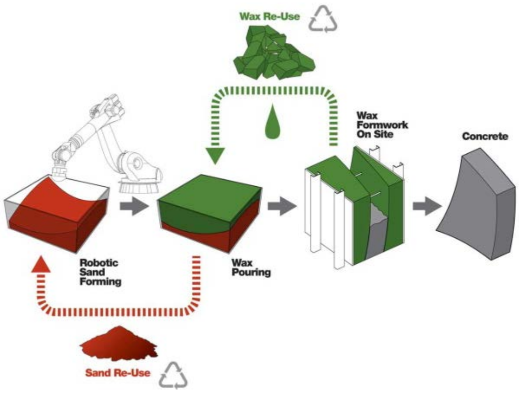


Fig 3.61 Wax as waste free formwork (copyright www.lafargeholcim-foundation.org)

Wax milling was developed with sustainable re-use in mind. This involved the machine milling of a hardened piece of wax to the desired mould curvature with zero-waste. According to Schipper (2015), invention patents were filed by Ahonen (1986) and Dittmann (1989) The use of special solidified wax as formwork is also investigated as *Tailorcrete* where special molten wax with a very high melting point allowed concrete to be applied to create three-dimensional surface investigated by Silvan Oestele at ETH, Zurich (Oesterle et al, 2012).

3.7.3 Earth Mounds

3.7.3.1 Teshima Art Museum, SANAA, Teshima Island Japan, 2010

Fig 3.62 Teshima Art Museum: The construction process uses a earth-mound as formwork. The earth was removed after the concrete pour by excavation.(copyright SANAA)

This idea was re-explored more recently in the impressive construction of Teshima Outdoor Museum in Japan in 2011. Designed by SANAA, the open-air building sits like a water droplet in the landscape on the island of Teshima. Dimensionally, the shell had a maximum span of 41.2m, a maximum rise of 5.12m and a thickness of 250mm. Professor Mutsaro Sasaki was the structural engineer for this project (Sasaki, 2010).

Fig 3.63 Teshima Art Museum: The open air shell produced exquisite spaces with a delicate relationship between the inside and outside. (copyright SANAA)

3.7.3.2 Heinz Isler

Earth mound formwork was used experimentally by Heinz Isler in early experimentations (Chilton 2000: p19, p144). This technology involved the preparation of earthworks to the shape of the shell. Once concrete has been poured onto the formwork and set, earthwork was removed to reveal a self-supporting concrete shell.

3.7.3.3 Binz Life guard station

For Muther's lifeguard station, at the shells at Binz (1975 and 1981), earth mound moulds were used. This was presented in Chapter 3.3.10 earlier.

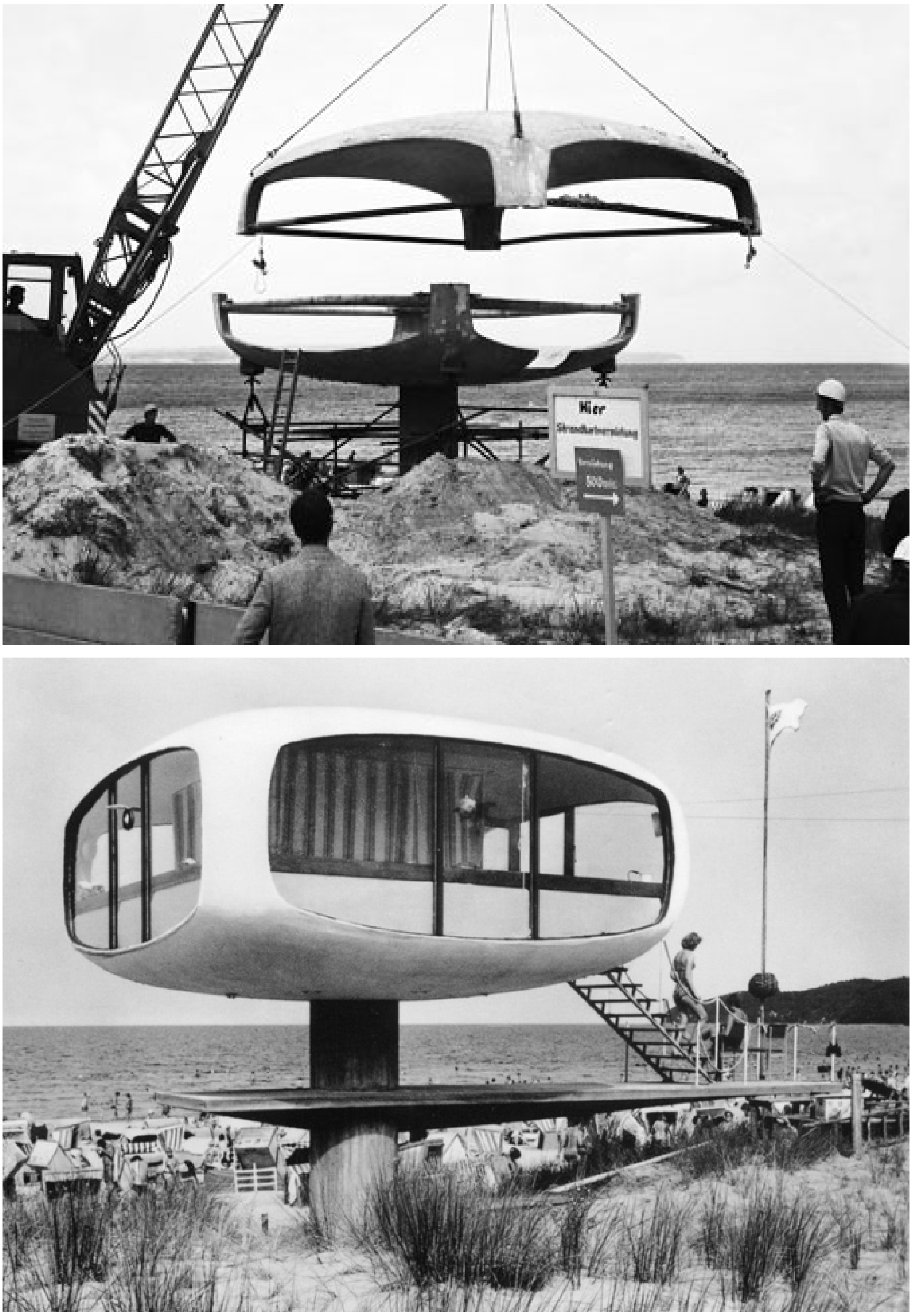


Fig 3.64 The water rescue station seems as a spaceship which is landed on the beach of Binz, on the Baltic Sea island of Rügen. (Photo copyright Müther archive)

Other Formwork systems:

3.7.3.4.1 Vacummatics

In the Netherlands, Dutch architects and engineers are also developing various formworks for the construction of thin concrete shells. One method was the use of vacuumatics to create three dimensional formwork systems developed by Huijben, van Herwijnen and Nijesse. By creating a vacuum in an enclosed membrane envelope with unbound particles within, three dimensional forms can be created to function as a temporary surface formwork for concrete (Huijben, van Herwijnen and Nijesse, 2012).

3.7.3.4.2 Pneumatic Wedge, TU Vienna 2014

In 2014, TU Vienna developed a system to create a concrete shells from flat plates. (Krosemer and Kollegger 2014). The Pneumatic Wedge Method of shell construction consists of a concrete slab resting on a pneumatic cushion. The flat formwork tray slab was wedged with spaces in between the segments so that when the middle section is lifted, the segments will fit together perfectly. A shell of a height of 2.9m was achieved within a lifting period of 2 hours.

Fig 3.65 Thin concrete elements lifted by inflation of a pneumatic formwork (copyright TU Wien, 2014)

Fig 3.66 Pneumatic wedge system (copyright TU Wien, 2014)

3.7.3.4.3 **Masonry Vault Shells, ETH Zurich**

At ETH, Zurich, researchers at Block Research in collaboration with MIT have been looking into digitized way to design masonry vaults with digital analysis and fabrication methods. Their Thrust Network Analysis (TNA) has culminated in the impressive Armadillo vault that was constructed from bespoke and precisely milled stones guided by computerized processes to form a stone vault at the Venice Biennale 2016.

Fig 3.67 Stone elements fitted together to form a vaulted structure (ETH, 2016) (copyright Anna Maragkoudaki)

3.7.3.4.4 Cable Net

Researchers in Holland and ETH, Switzerland are exploring ways to construct shells using cable nets as formwork. This is based on the idea of the cable net supporting concrete upon which concrete is poured onto. This idea was proposed for the Waal Bridge design proposal by ZJA architects illustrated in fig. 3.68.

Fig 3.68 Model of the extended Waal Bridge : The initial construction proposed a formwork of cable nets supporting fabric membrane to contain concrete for this project. Unfortunately this was not followed through and timber ply shuttering were used instead to create the bridge. (copyright: ZJA, Amsterdam)

As well, the use of tensile formwork to support a fabric surface formwork was explored for the construction of the NEST Hi-LO project at ETH Switzerland (Veenendaal and Block, 2014). This is a shell concrete roof constructed by applying concrete on a fabric stretched over a net of tensile cables. It offers potential to create interesting shapes and forms for creating force-active shapes. This will be discussed in more detail in chapter 4.10.8

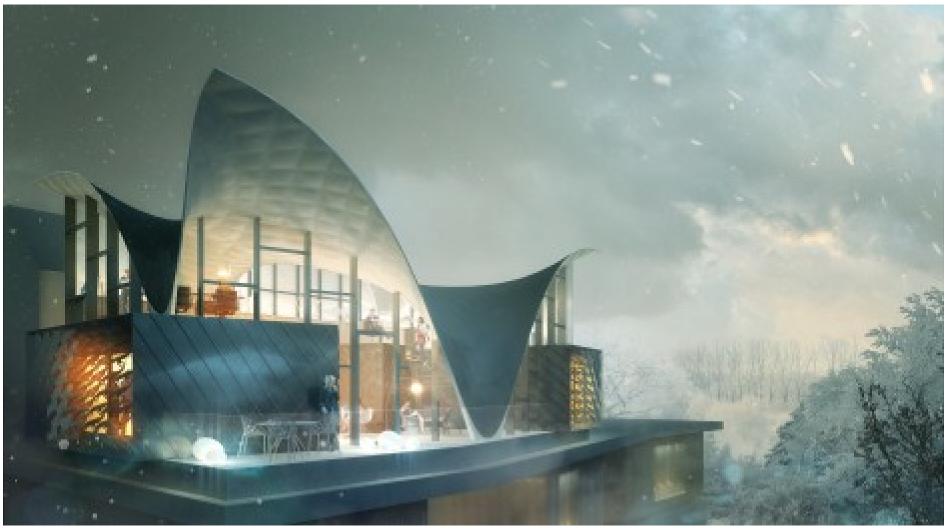


Fig 3.69 NEST Hi-LO project that employed tensile cables for applying wet concrete onto in a thin layer to produce a shell. (http://hilo.arch.ethz.ch and Doug Wolf)

Analysing the system of the cable-net system, disadvantages associated with it are clear to identify. Firstly, in order to suspend this cable net, a frame strong enough to sustain the tension forces as well as the dead-weight of concrete applied onto this surface need to be designed and built. Secondly, to ensure the desired form was achieved, it was time-consuming to adjust each cable element. Thirdly, the processes of form-finding and structural analysis appear complex suggesting the involvement of specialist skills, adding to cost. Fourthly, once removed, the formwork system may not be re-used, and if re-used, have to be laboriously removed individually. Although ingenious in concept, deficiencies and disadvantages still remain.

The following section presents some associated ideas of creating concrete/ masonry shells and/or vaults.

3.7.3.4.5 Catalan Vaulting

The method of construction developed in Mediterranean Spain presents development and artistry of constructing sophisticated double-curving thin shells using lightweight terracotta tiles. The art of vault building by laminating terra cotta tiles, often without the need for centring or formwork was developed from Valencia to nearby regions eventually exporting to the United States with Rafael Guastavino (Oschendorf, 2010: p30). These structures pertained to efficient funicular vaults made through a union of a close material and tectonic understanding.

Fig 3.70 Guastavino vaulting being constructed.
(http://krisdedecker.typepad.com/photos/uncategorized/2008/11/10/guastavino_1.gif)

What makes this construction method attractive is the redundancy of centring or intermediate supports. This relied on a high degree of skilled workmanship by the artisan who would construct shell vaults by skillfully laminating layers of thin terra-cotta tiles or brick to produce intricate vaulting. The elimination of centring removes the two key barriers to these structures - complex formwork, time and cost.

3.8 Key Considerations on Concrete Shell Construction

3.8.1 Concrete mixes and application techniques.
The composition of the concrete mix and method by which concrete is applied to prepared formwork impacts on suitability/ assessment and formwork choice. Listed are some important points to consider:

3.8.2 Concrete Mixes: Concrete is a combination of cement, aggregate, sand and water. Additives can help achieve different strengths and mechanical properties of the concrete. Reinforcements in the form of steel, glass fibres or synthetics can also be added to change mechanical properties of the resultant concrete. The amount of water alters viscosity whilst chemical accelerators or retardants can change the amount of time the concrete mix will take to set.

UHSC (Ultra High Strength Concrete) is created by the addition of superplasticisers, quartz powder and other constituents. The concrete can achieve very high strengths, from 100 to 200 MPa in compression and more than 40 MPa in flexural strength, shear strength improved, high resistances in impact as well as repeated loads. This has cost implication but allows an improvement of structural performance to be achieved (Stacey, 2011: p 23).

Hand trowelling is the most conventional method of applying concrete onto shells. The ready supply of cheap manual labour in Mexico and war-time Italy allowed Candela and Nervi to build shells cheaply in Mexico and Italy. In less developed economies, this is attractive and required unskilled labour. In these scenarios, the quality and thickness of the concrete shell may require more monitoring.

Sprayed concrete (gunnite or shotcrete) is an alternative to applying concrete manually with trowels. Traditionally used in tunnels and other groundwork projects, concrete is pneumatically projected through a pressurized nozzle where mixes can either be dry or wet. In the dry method, water is combined with the dry mix at the nozzling stage while the wet method projects an already hydrated mixture onto the surface. Depending on the amount of water added, viscosity can be controlled. Therefore, this method is suitable for applying concrete evenly, even at in-accessible areas, in upside down positions and/ or large areas. The addition of steel, glass or synthetic fibres can also alter the workability and consistency of the sprayed concrete. Steel reinforcement (staples) can also be added into the mix to improve tensile strength. The Balz House by Heinz Isler (Balz, 2012, p3) (Bosiger, 2011, p169) for example was created with sprayed concrete. This method however presents problems of concrete wastage in the form of rebound and a 10% loss of material should general be taken into account in estimating concrete volumes (Bill Jones, Sprayed Concrete Association president 2016).

3.8.3 Sacrificial Formwork

Although the “shells” of Vittorio Giorgini (Florentine architect who was Professor at Pratt Institute), were not true shells i.e. as pseudo-shells or improper shells, his free use of concrete supported by wire-mesh created interesting shapes and possibilities. Giorgini used an iso-elastic membrane made of wire netting and concrete. The Liberty Centre constructed by him and his students at upstate New York created mesmerising forms. The project unfortunately suffered a lack of funding and could not be concreted (Giorgini, 1996).

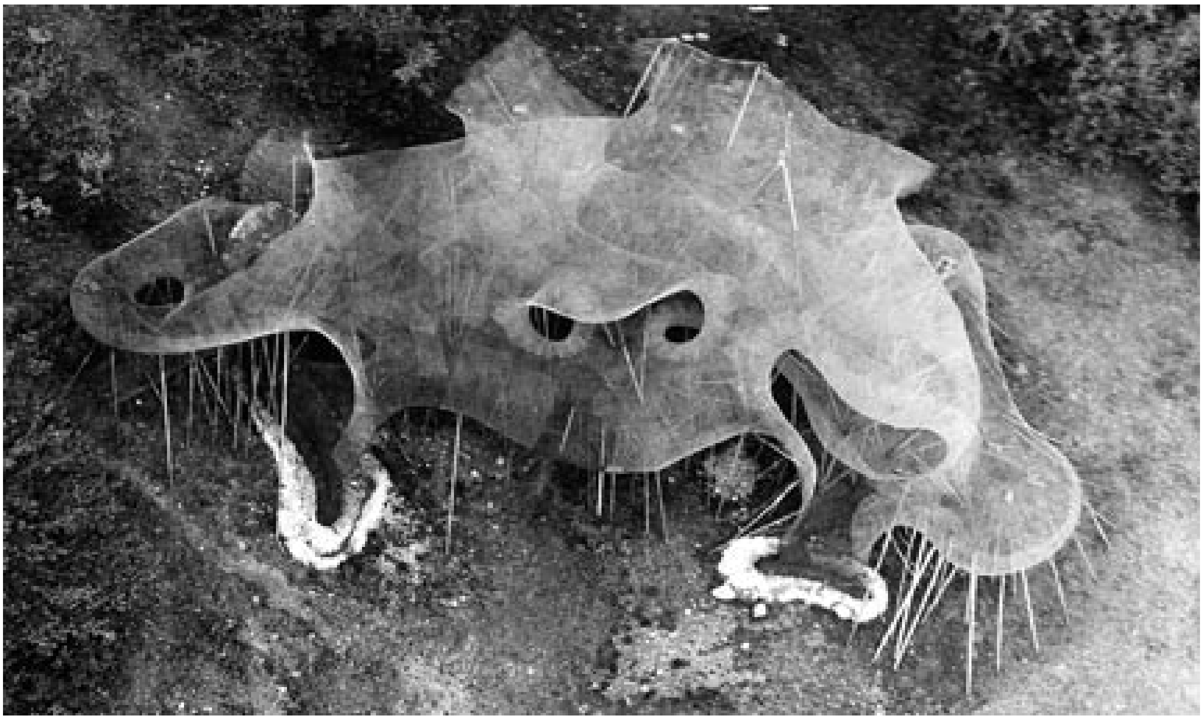


Fig 3.71 Liberty Centre at Upstate New York created and built by Vittorio Giorgini in 1976 (copyright Vittorio Giorgini Archives).

Fig 3.72 Liberty Centre at Upstate New York created and built by Vittorio Giorgini in 1976 (copyright Vittorio Giorgini Archives).

Comparison of Technologies (Formwork and Formwork Preparation) of Concrete Shell Forming

method	**manual labour required (formwork preparation and concrete application)**	**machining and tooling (formwork preparation)**	**cost of system**	**shaping speed**	**form freedom**	**surface quality**	**reuse of shaped elements reuse**	**recycling of raw material**
straight rigid timber planks (e.g. Candela)	high, usually on site	very low-tech, readily available saws and nails	low	slow	limited to ruled geometry (e.g. hy-par)	variable (shuttering usually visible)	traditionally re-used	yes
glulam profiled sections (eg Isler)	high, on site or in factory	high-tech, bespoke mechanised	high	slow	limited, bespoke	high but depends on surface material	yes, if same shape	yes
CNC Milling of tables to form casting surface (eg.Rolex Centre)	limited, usually in factory for machine control	high-tech, bespoke and specialised	high	fast	limited and bespoke to CNC tables milled.	high but depends on surface material	not usually as bespoke but possible if same shape	yes
pneumatic formwork (e.g. Bini, Monoliths)	limited, during erection of inflatable shape	cutting patterns/ sewing/ bonding	moderate	fast	low, limited to controllable pneumatics	high	yes, if same shape	partially
concrete fabric formwork (e.g. West)	high, bespoke for each casting	cutting patterns/ sewing	low	fast	limited to controllable form-finding	high	yes, if for same shape	partially
pre-cast concrete elements (e.g. Nervi)	limited, due to repetition	repeated mould-making	low	N/A	limited to controllable formfinding	high, depends on finishing material	yes, if for same shape, but not usually	yes
earthmound formwork (e.g. Teshima)	limited with the use of mechanised equipment	large scale machines for moving earth	high	slow	highly flexible in freedom of form	depends on detailing	yes	partially
cable-stayed supported fabric formwork (eg Hi-Lo)	limited, bespoke and set up of cable-net and membrane	specialised machines and requires frames to install the formwork	Low But design cost may be high	variable depending on situation	limited to specialist digital formfinding.	high	partially	partially

Table 3.2 Table of a comparison of formworks (adapted from Schipper, 2015)

3.9 Discussion: A critical analysis of traditional and current shell construction methods

The table 3.2 above compares all available concrete shell formwork possibilities. This shows a complex matrix of pros and cons of each method of shell forming to various degree of effectiveness.

For straight timber planks, in economies with low labour costs, this is more commercially viable. Fabric formworks, as soft and flexible formwork will be discussed in following chapter 4, offering options such as pneumatics which can be quickly inflated and be reused but may be monotonous.

Timber planks seem to offer largest form possibilities but are very intensive in labour. Although glulam profiled sections could produce high accuracies, they can be bespoke and costly. Although recyclable, they are only useful when the desired shell shape is repeated. The survey has found the surface quality variable as well.

Many of the early shells were dangerous to build. Photographs taken of the construction process evidenced labourers precariously balancing on doubly-curved timber formwork and spreading slippery concrete at a high level (fig. 3.45). The issue of construction safety is a contemporary consideration that designers and builders need to address.

CNC Milled tables such as those used for Rolex Centre and Kakamigahara Crematorium require specialist machines and labour expertise which could increase front-end labour costs. It is a very high tech approach to fabricating concrete shells to great accuracy. The formwork can become excessively expensive compared to concrete. In the case of the crematorium casting, the designers took away from the hands-on approach of the crafts person. This is especially true in the dematerialisation of concrete in Kakamigahara pointed out earlier with board marking literally erased from the finished product. Although materials for making milled tables can be OSB recycled timber board products; because of their bespoke nature, they cannot be completely re-used.

Again, simple fabric formworks which are stitched to shapes will be bespoke to each casting. The limitation of this is the need to have a framework that supports the fabric.
Unless panels are repeated, liken to Nervi's shells, the use of repeated pre-cast elements may not be as flexible and as reconfigurable in terms of form results.

Although earth mound formwork is an exciting development, their application may be limited a large amount of easily moved earth readily available in most building sites. There are to main applications of this, first, to use earth mounds as casting moulds to cast concrete shells after which artefacts are moved and assembled to form complete shells. The second way to use earth mounds is the large scale where the shell is cast in site. In the case of Teshima Art Museum, this meant removing the earth from underneath the shell needs to be factored into the procedure design (through the incorporation of two holes large enough for trucks to pass through).

The following section is themed under each criteria discussed in Table 3.2

3.9.1 Labour cost

Although concrete is not an expensive construction material, factors such as labour and design costs impact indirectly on cost. In a price sensitive construction market, the total cost of formwork types, construction system and the amount of specialist design time need to be carefully considered. Discussed earlier, the ready availability of low cost labour helped Candela to popularise concrete shell use. The extent by which a labour-intensive system is used depends very much on the economic situation of the country.

Since 1963, R.A. Sundarum has designed numerous thin concrete roofs in his native India. Speaking at IASS conference in 2012, he attributed his work on the continued availability of low-cost labour in India sustaining his work (Sundarum, 2012). With labour cost remaining cheap in India, his office continues to design and construct concrete shells to this day.

Although factory manufactured, glulam timber sections can be labour intensive as contractors are needed to assemble sections of glulam timbers together on site. In the same way, the mechanised process of CNC milling of “tables” for concrete pour, still relied on human labour to construct them on site as demonstrated by the casting process at Kakamigahara Crematorium and also at the Teshima Art Museum. Additionally in these systems, human input in control to concrete thicknesses is crucial to achieving the desired impression of thinness.

In pneumatic and fabric formed concrete methods, bespoke formwork demands a human element of craftsmanship. Whilst on site, workers would still be required to secure inflatable formwork onto the floor and check for air leakages. Manual labour and human supervision is required to ensure any snags could be dealt with during the erecting process. Subsequently, the intensity of required labour will also add to project cost.

3.9.2 Design and construction costs

Not only do installation costs have an impact, specialist design and construction contributes to the high cost of this system. The highly complex designs require specialist design input, lifting cranes, machineries and extensive scaffolding can quickly erode the low cost of concrete.

3.9.3 Speed of Formwork Preparation and casting

The speed and complication of a shell system is a prime consideration. To be able to set up/ decentre and re-assemble formwork system rapidly and efficiently is crucial. Naturally, this also has an impact on cost.

3.9.4 Shape Limitation

Pneumatic formworks suffer from shape limitation as resultant concrete shells are monotonously dome shaped. Glulam formwork sections, although bespoke to the shape of the shell may only be used once, unless repeated forms are required. With CAD/ CAM technology, temporary and cheap OSB/ plywood formwork are assembled rapidly. To counteract this limitation, Candela used ruled geometries in hyperbolic paraboloids that allowed the easy use of straight timber planks. This reuse of cheap timber planks enabled Candela to design spectacular repeated shells such as the radiating Los Mantiales in Xochimilco (1958), Church of Our Lady of the Miraculous Medal (Iglesia de la Medella Milagrosa (1953-1955) and the roof at the Coyoacan Market in Mexico City (1955).

fig 3.73 the use of straight planks used extensively in the construction of Candela’s creations in Mexico.

3.9.5 Surface quality

This is dependent on many factors such as the finishing/ lining materials, concrete mix and construction method. Most of the concrete shells discussed here are exposed, although most of Candela's shells were painted. Concrete finishes and societal acceptance of such surfaces play a major role in the popularity of concrete shells. Fabric formed concrete columns and shells required an understanding of concrete's intimate interaction with fabric. For example, concrete vibrating techniques for the right amount of time brings about smoothness to the fabric surface of the fabric formed concrete.

3.9.6 Formwork Reuse

"…….a shell structure can successfully compete with other forms of construction whenever a well-designed structure can be built in a planned manufacturing cycle with the effective reuse of centring and forms."

Felix Candela (Garlock and Billington, 2008)

The ability to be re-used is a crucial factor in our resource-sensitive environment. When formwork is reusable without affecting design and concrete quality, it becomes an attractive asset. Fabric formwork and timber planks of Candela were reused. Isler used stored-away timber formwork repeatedly to make shell building more sustainable and economical.

Re-configurability of formwork

This is useful when the project consists of repeated identical forms. If shell formwork system can be re-configured to create other shell-forms, this adaptability will address many shortcomings that also led to the demise of concrete shells.

Recycling of formwork material

When components of formwork systems can be recycled, processes embodied within the application of concrete shells can respond to the need to produce an environmental building system.

How intuitive is the formwork system?

Because concrete shells are the result of the complex interaction between shape and forces, designers need to form-find shapes that best fit the site, work environmentally and look good, amongst other complex requirements. A way of instilling structural intuition of form and design parameters specific to each brief will make the concrete shell design less intimidating to the designer. If a system could offer an understanding to how different curvatures enhance structural integrity, the designer, whether architect and/or engineer, will be able to design concrete shells that address the concerns of economics, aesthetics and efficiency.

3.10 Summary

Chapter 3 has investigated key ideas associated with the technology associated with concrete shells, forming an overview of this architectural technology:

- The existence of two types of shells: Proper (pure compression, form-active) and Improper shells (which have bending moments in abundance, also known as pseudo-shells (Mutsuro, in Adriaenssens et al. 2014).
- Presented a history of shells development using seminal figures and key case studies over the last 9 decades
- Presented an overview of shells acceptance in society through a survey of social, cultural and economic factors.
- Presented the geometrical classification of shells
- Explained the key considerations of concrete shells
- Discussed the methods of constructing concrete shells, especially with regards to rigid formworks.

3.11 Conclusion

Evidently, through this review of concrete shells, their rise and fall in the 20th century was intrinsically linked to the way they were designed and built. As well, they are closely associated with their formwork system. Competition from alternative structures such as highly adaptable steel frames meant that concrete shells which required complex design, with cumbersome formwork and time-consuming to build, concrete shells as an architectural solution quickly lost out of favour. Other systems readily offered flexibility for structural adaptation, and allowed light to filter into the spaces beneath. Although concrete was a cheap material of construction, the construction method were not economical and the formwork difficult to work.

Once again, when compared to steel frames and other lightweight structures, concrete shells seem less attractive.

Various research groups and companies have attempted to develop systems to address issues of formwork re-use and re-configurability. Additionally, using computer softwares at preliminary stages as a digital exercise can be less intuitive to the designer which easily deters architects from trying to design with shells. A thorough survey of shell design and construction methods have highlighted a missing gap for a single system that is reusable, reconfigurable and intuitive (to design with).

The findings and analysis therefore suggests that to rejuvenate commercial interest in concrete shells again falls onto the remit of a new formwork system that is fast and easy to erect, with the possibility of being reused and be re-configured to produce a variation of forms. This flexibility and potential of re-use with a variation of forms and ease of design is yet to be demonstrated by current shell formwork systems.

This quest for a suitable formwork system motivates the application of deployable gridshells as re-usable, re-configurable and yet intuitive for the designer to understand the forces and the construction process.

Complementary to this idea in the search for a suitable formwork system, sees the use of textile fabric as an efficient way of creating shells. Textile shuttering as soft and flexible methods of constructing concrete shells will be discussed in the next chapter. This sees fabric formwork used as concrete shell formwork. This use of fabric as formwork is a key component to the technology that supports the idea of gridshells as formwork proposed in this research.

Fabric Formwork Workshop, Nanjing Southeast University, China, 2016 (Gabriel Tang)

PART 2 THE CONFLUENCE OF TECHNOLOGY

Chapter 4 FABRIC FORMWORK

Chapter 4: Fabric Formwork

A flexible fabric, or membrane, resists imposed forces in pure tension, which is the single most efficient way to resist a force. Rigid moulds resist force through bending – a far less efficient mode of structural resistance.

A flat, rigid mould is a zero-deflection structure, which means it must work very hard to keep everything as flat as possible. This requires a high degree of stiffness, which inevitably leads to formwork structures of much greater depth, and hence greater material volume and weight. A flat, rigid mould fights against the forces imposed by the wet concrete, but a flexible mould actually uses those forces to produce the most efficient mould shape possible. We can say that flat formwork panels dream of having the curves of a pressurized fabric mould-wall.

Before being filled with wet concrete, a slack fabric mould is largely indifferent to its shape – its form in space remains flaccid and variable. But when these two more or less amorphous materials are combined, they hold each other in a mutual embrace, producing an energized system of burden and restraint.

West, 2016

"…….state to inform the final result of the operation led logically to working with a responsive shuttering medium, with the technical challenge of restraining a fabric against the hydrostatic pressure of concrete the focus of experiment. "

Chandler, 2004

4.1 Introduction:

To provide surface support for concrete to be cast onto deployable gridshell formwork, fabric is stretched over the temporarily braced rigidified gridshell. The technology of using fabric as concrete support will be discussed and explored here to give an overview of this technology.

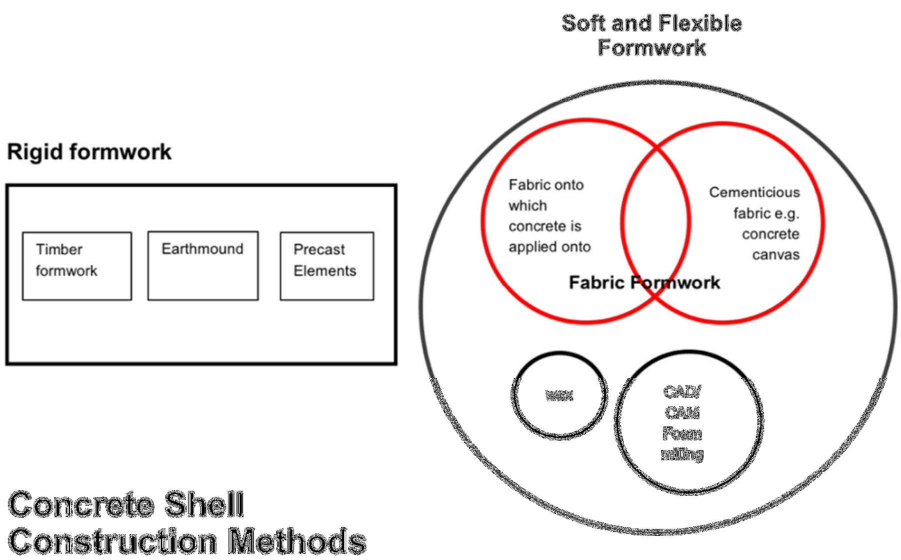


Fig. 4.1 Fabric formwork is classed under soft and flexible formwork in all formwork available for shell casting

In earlier chapters, possible ways of creating concrete shells using rigid formwork (timber formwork, earth mound and pre-cast elements) were presented. In more detail, soft and flexible formwork in the form of fabric would be discussed as one of the three pillars of this work.

Fig. 4.2 top: Wall at MOMA by Andrew Kudless, 2009 (taken from: http://matsysdesign.com/2009/08/11/p_wall2009/) Bottom: The Buenos Aires bench, 2010 by Grupo Bondi, Argentina look soft, warm and fabric like, are in fact cold and hard concrete (copyright Gabriel Tang)

Our encounter of fabric as formwork often rests on resultant artefacts that suggest their use. Not often immediately revealing the way they were made, fabric-formed concrete often intrigues as it looks soft and fabric-like, but feels hard and rigid, rather counter-intuitive to our expectation. This discrepancy is exemplified by the artistic installation of Kudless's Wall at MoMA (2009) where a large section of a wall was clad with bulbous concrete inflated forms. On the other hand, the Buenos Aires bench (2010) was commissioned as a collection of side walk furniture in the Argentine capital. As can be seen, this technique effectively combines two main materials - concrete and fabric to express process and forces in the way hydrostatic fabric formwork deflect between restraining points to create catenary forms (Manielius, 2012 and Chandler in Chandler and Pedreschi 2008).

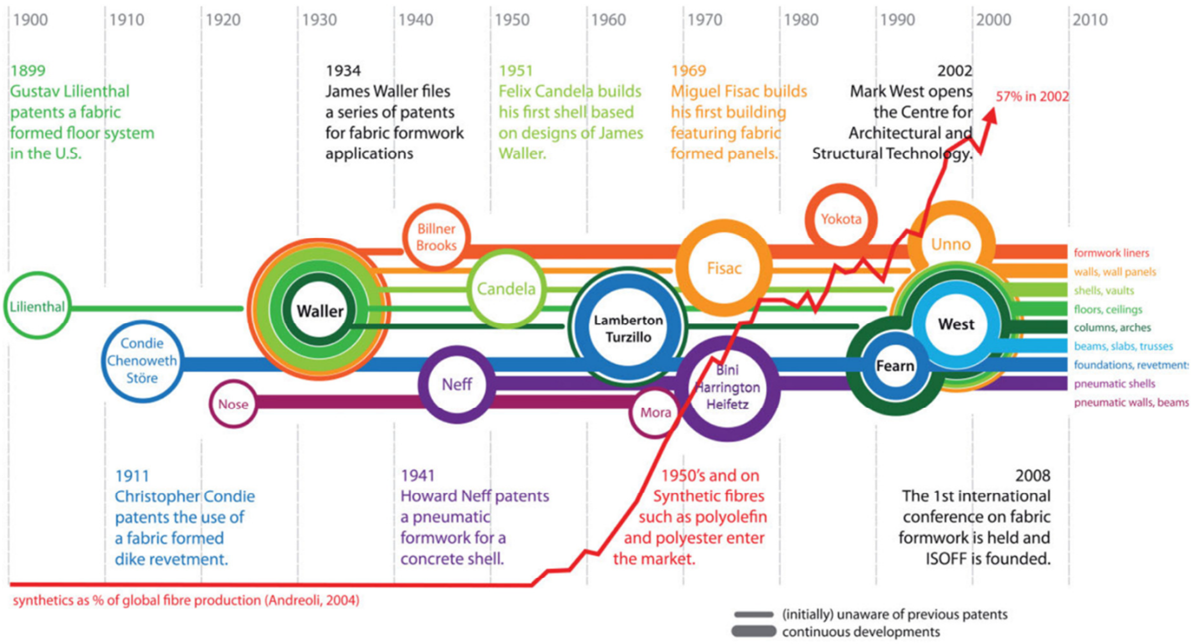


Fig. 4.3 A Chronological diagram of fabric formwork and formwork liners Andreali, 2004, taken from Veenendaal, Block and West et al, 2011.

The history of this idea is represented by a chart extracted from Veenendaal, Block and West (2011) highlighting key figures in the genesis and development of this concept beginning with the US patented flooring system of Lilienthal in 1899. The chart also shows a start of synthetic fibre production from the early 1950s. Many of the featured figures such as James Waller, Fisac, Bini, Unno and West will be discussed in the following sections to illustrate this evolution from the late 1800s until the present day.

4.2 The advantages of using fabric formwork:

(**https://sites.eca.ed.ac.uk/fabricformedconcrete/fabric-formed-concrete/**)

Fabric forming *"reveals a synergy between fabric and fresh concrete. The concrete gives shape to the fabric by its weight and then receives the form and surface the fabric produces in return"* Pedreschi in Pedreschi and Chandler (2007). This is not only about shapes alone, the interaction between the "responsive shuttering" and results are important ideas as well. Another advantage of using fabric form-work, is sustainability when compared to other formwork options.

Due to significant savings on formwork, production, storage and transport, with reusability (Lee, 2011, Orr, 2012, West, 2016), this may lead to numerous advantages such as:

4.2.1 Low cost.

The placement of wet concrete on fabric results in the most optimised shapes that carry the weight of the wet concrete with minimal requirement for bracing.

4.2.2 Improved concrete quality

Porosity of membranes allows excess air and water to escape to reduce imperfections in casting such as bug holes. This improves the finish of the cast concrete, seeing improvements in strength and density of the concrete, thereby improving durability.

4.2.3 Structurally efficient forms

The flexible nature of fabric allows wet concrete to produce geometrically efficient forms that carry the dead weight of the concrete with variable cross sections. Compared to prismatic formwork, fabric formwork facilitates the reduction of deadweight of an efficient structure.

4.2.4 Finish.

As the finish of the fabric formed concrete is controlled directly by the fabric itself; it was therefore possible for the designer to determine the finish quality by using fabric with different textures and structural properties.

4.2.5 Connection details.

Construction accuracy and precision is important in all constructions. As it may be difficult to control the precision of the actual cast, connection details and edge details will need to be designed carefully to ensure various components can be connected accurately if using fabric formwork in sections.

4.3 Early Applications

Increasingly, fabric formwork application has crossed the boundary from the geo-civil engineering realm into architectural applications. This technology is utilised in ditch/ trench construction as well as railway cutting /marine coastal uses. To produce heavy-duty, durable, soft and flexible formwork, high tenacity nylon yarn textiles were stitched and filled with concrete to create a variety of useful forms shown in fig.4.4. The main drivers were not based on aesthetic needs but by one of the practical means of being filled rapidly and effectively.

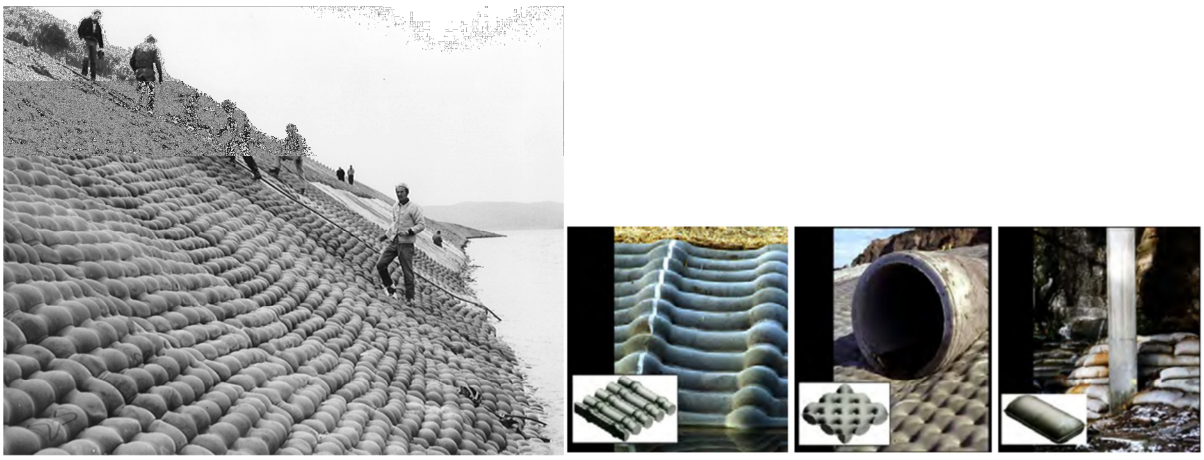


Fig. 4.4 Fabriform: left: Commercial systems were installed in 1967 on the Kinzua Researvoir, New York in 1967 and right: in utilizes fabric woven of high tenacity nylon yarn into a variety of forms that stabilized river banking shown here. (taken from http://www.fabriform1.com)

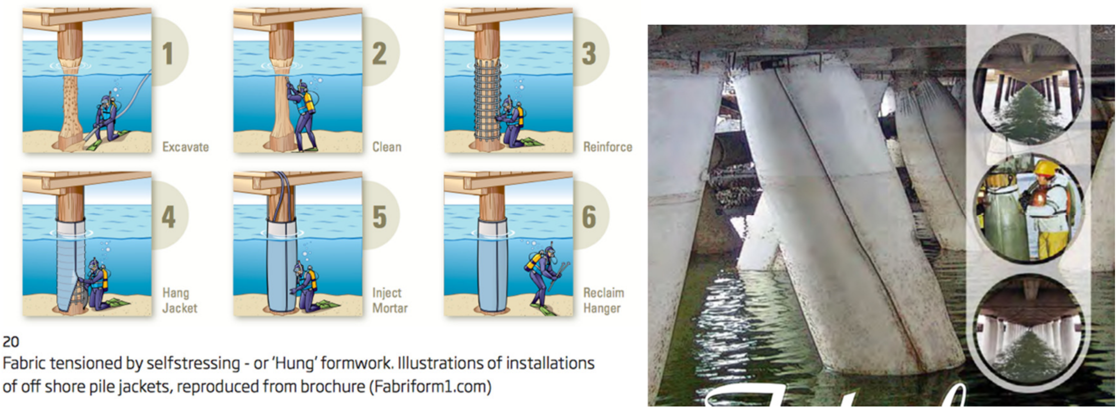


Figure 4.5 The fabric formwork – Ballistic Pile jacket is designed to allow corroded underwater piles to be repaired by introducing fabric sleeve to contain the concrete (taken from http://www.fabriform1.com).

At a practical level, fabric formwork collars can be wrapped around a corroded ocean pier to contain concrete which is poured into the formwork to repair the corroded pier sections.

4.4 Fabric Formwork vs Prismatic formwork

Fabric formwork has many advantages over conventional prismatic formwork.

1. Fabric formworks are structurally more intuitive as fabric draping behaviour and loading conform to loading statics i.e. Hooke's Law e.g. draping shells generated by West (2016)
2. Fabric formworks being lightweight are therefore more easily portable. For example, the formwork for the concrete columns at Casa Dent was freighted in three luggage duffel bags from Winnipeg, Canada to the Island of Culebra (West, 2016).
3. Material Savings. Fabric formwork, through gravitational interactions produce forms which are as strong as their prismatic versions with savings to material and cost - see 4.6 below.
4. Additionally, fabric formwork offers an honest form of architectural expression true to their construction process.

4.5 Material Saving:

Fabric formwork allow for the optimisation of materials (concrete). According to research by Orr (2012), using fabric to cast concrete columns has the potential to reduce concrete material usage by up to 40%. Along with form optimisation, less resources is used to transfer forces with more efficiency and effectiveness. Therefore, material saving may result in cost and resource reduction.

4.6 Modes of Application: Filled and Surface molds

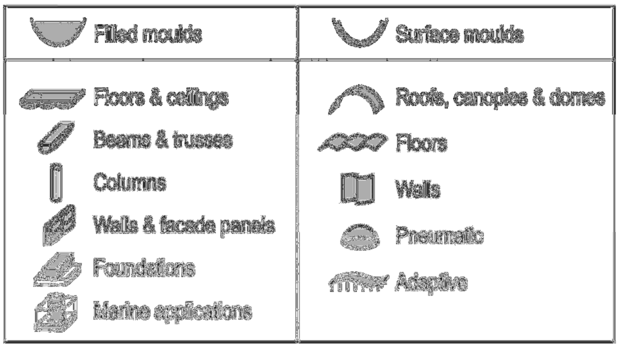


Fig 4.6 courtesy of flexibly formed structure classification (adapted from Veenendaal et al. taken from Veenendaal, D., West, M., Block, P. 2011)

Formwork is used in two main ways according to Hawkins, W. J., Herrmann, M., Ibell, T. J., Kromoser, B., Michaelski, A., Orr, J. J., ... & Veenendaal, D. (2016). They are namely as filled moulds, or as surface moulds.

As filled moulds, they can be used to form different elements of the building structure such as:

on floors and ceilings
beams and trusses
columns,
wall façade panels,
foundations and
also in marine situations.

As surface moulds, fabric formworks can be used as:

roofs, canopies and domes,
floors, as walls,
pneumatic formwork and
adaptive moulds.

4.7 Surface moulds application:

The following section further explains four different uses of fabric formwork as surface molds, of particular relevance to this study. The four different ways to use fabric formwork to cast a thin concrete layer on top are by:

1. **Free Hanging Formwork**
2. **Pre-stressed fabric formwork**.
3. **Pneumatic.**
4. **Pre-cast elements (using flexible mould)**

4.7.1 Use of Free Hanging Formwork

Formwork can hang freely under gravity. Under self-weight or weight of freshly applied concrete, this allows the fabric to find the most efficient form. However, it may be difficult to flip the concrete shell around due to their weight, as exemplified by difficulties experienced in casting draped shells after they were constructed at The Centre for Architectural Structures and Technology at The University of Manitoba (West 2016)).

Fig 4.7 (top) Fabric Formwork were first rigidified to create a funicular shell mould which was turned upside down and then concrete cast. (bottom) A 3cm thick, 5 metre long fibre-reinforced shell is being turned over (copyright West, 2016)

At The Centre for Architectural Structures and Technology (University of Manitoba), Mark West and his collaborators explored creating thin shells spanning between 2m and 5m. Referring to fig. 4.7, they did this in two ways: Firstly, the fabric was stretched between two edges. Then, they were loaded with a thin layer of spray plaster. When this is hardened, the temporary plaster shells would be turned upside down and used as inverse molds onto which concrete was applied to create the concrete shell (West, 2016). Although the experiment has proved the difficult nature of "flipping shells" that introduces large temporary bending stresses (which may crack or facture the shell), it was also very cumbersome to invert a heavy and awkwardly shaped three-dimensional shell (West, 2016).

4.7.2 Application of concrete onto pre-stressed fabric formwork

A thin layer of wet concrete can be applied to a pre-stressed surface stretched to provide a degree of stiffness. James Waller's shells, for example, are built by hessian pre-stressed over frames and covered with concrete.

Ctesiphon Vaulting work by James Waller

The concept of applying concrete to pre-stressed fabric formwork resonates with the hypothesis. As such, elements of his work are of special interest and relevance.

Fig 4.8. Taq-I Kisra arch at the ancient imperial city of Ctesiphon (http://techniker.oi-dev.org/blog/view/engineers-cowcross-gallery-talk)

Born in Tasmania in 1884 to Irish parents, James Waller returned to his parents' homeland of Ireland to pursue a degree in engineering at Queen's College Galway and in Cork. During World War One, Waller served in the Mediterranean. Stationed in Salonika, Greece, he observed how cement dust blown onto a wet tent fortified the canvas. He experimented on this idea and perfected this technique, patenting it the *Nofrango* technique. Subsequently, during his 1922 visit to Iraq, Waller visited the *Taq-I Kisra* arch at the ancient imperial city of Ctesiphon. Impressed by what he saw, he called it "the first column-free rectangular building of importance", as being a funicular stone arch implied its structural efficiency. He was protective and defensive of the funicular arch-form stating "gravity was destructive to the beam-truss-girder family, but bestows stability upon the arch" (Ross, 1975). He set out to revive this form and "rescue the arch from comparative obscurity".

Fig 4.9 top row: Ctesiphon shell construction for an 18 m (60 ft) experimental building for H.M. Ministry of Works, 1948, Barnet, UK (Waller and Aston 1953 from West 2016)

Waller invented a construction method to create shells with corrugations (formed by gravity) which gave the structure additional stiffness. He was reminded of the roof construction of a chicken coop with stretched hessian sagging between supporting timber poles. This inspired him to invent a new concept of construction which he called Ctesiphon Vaulting, after the Ctesiphon Arch. He allowed the fabric to sag to gravitational pull between funicular shaped formwork to form transverse corrugations along the length of the shell to provide additional structural stiffness. This method minimised the amount of reinforcement required to construct the shell. Indeed, this was a very appealing form of construction at the time of steel shortage.

As it was a simple method of construction, the structures required only unskilled labour, and these shells could be built quickly with little need for sophisticated mathematical calculation. Waller wanted to create a new tectonic expression for concrete shells. He revolted against the borrowing of textures and qualities of timber formwork, noting that "engineers are frequently unkind to their treatment of concrete, impolitely regarding its aversion to tensile stress" (Waller, 1935). To Waller, the tactility and structural capabilities of concrete was special and specific to the material. He felt strongly that structural capability must be celebrated through its construction.

During the war, there were 50 such concrete shells built with spans between 6m and 12m. (Veenendaal et al, 2010). A variation of this came in the form of granary domes in Cyprus, also known as the Cyprus bins. A patent was granted in 1955 for spans of up to 150m. This technology was applied in applications between the 1940s and 1970s, in housing, storage and factories around the world in countries such as UK, Ireland, Zaire, Zimbabwe, Tanzania, Nigeria, Kenya, Australia, Spain, Greece and India.

Fig 4.10 Top left: construction of a small scale protype. right: fabric and concrete in a mesh construction. middle: workers clamber onto the vault using temporary timber beams (Irish Architectural Archive courtesy of http://cargocollective.com) bottom: Cyprus bins being constructed for grain silos Cyprus bins for storage of grain or maize in Nicosia, Cyprus, built 1954–5, and construction for those in Nakuru, Kenya, built 1966–8 (a: courtesy Robert Emery, Department of Agriculture and Food Western Australia; b: copyright Grant Maslen)

Waller's method of creating concrete shells was not only highly assessable to those who wanted to build cheaply and efficiently, using low technology, the impact of Waller's systems on one of the key shell builder in the 20th century, Felix Candela, was also profound. In 1963, Faber wrote that Candela hated clumsy and unreliable solutions forced to fit preconceived ideas. The Ctesiphon method offered a structurally intuitive way of resolving structural problems. In fact, this led to Candela's initial ideas about using hypars to impart stiffening in his shells. It was widely accepted that Candela selected the

Ctesiphon method for his first experimental vault in San Bartolo, Mexico (Faber, 1963). The Ctesiphon system was used again in a rural school near Ciudad Victoria in 1951. Evidently, Waller's work had a big impact in the development of shells.

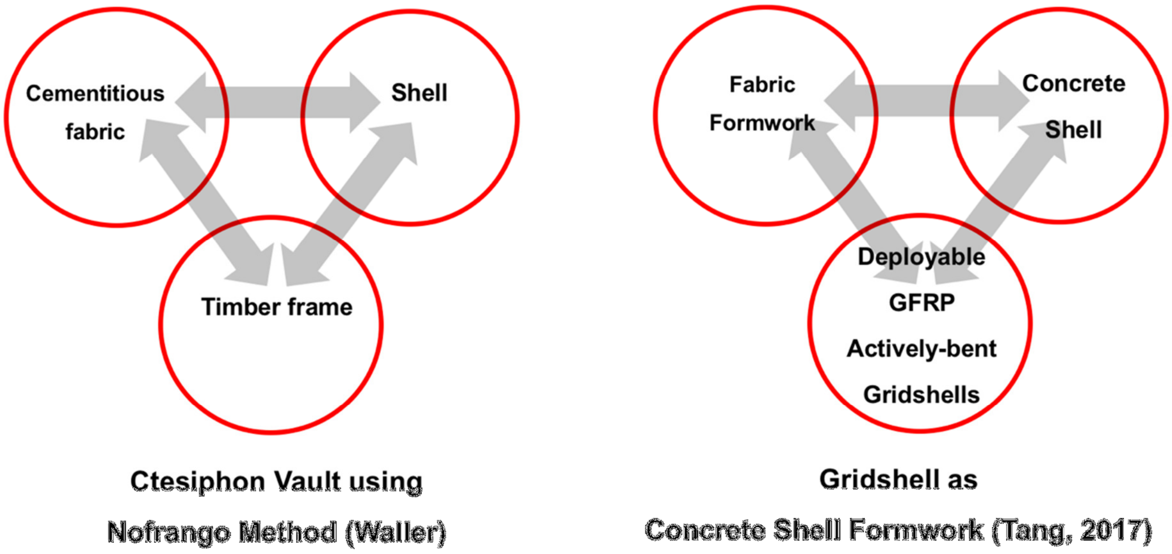


Fig 4.11 The relevance of Waller's ideas to this research inquiry

The relevance of Waller's method to the PhD

Waller's invention conceptually combined three technologies for the Ctesiphon vaulting innovation. Firstly, he used pre-stressed timber frames. Onto this, he attached cementitious flexible fabric which he allowed to drape to form stiffening corrugations. To prevent funicular formwork from deforming, they were cross-braced with timber laths to maintain these curved formworks. These temporarily restrained frameworks were often re-used. This closely mirrored the conceptual idea of the PhD where the deployable gridshell supported the fabric onto which concrete was applied.

In many ways, this idea is revolutionary as strong doubly curved shells could now be built quickly in a very specific economy (Conlon, 2012).

Unfortunately, the buildings he created, like the Bini shells (chapter 4.8.3), suffered from the monotony of form as they were of the same shape. As the forms were intrinsically linked to construction method, shell forms were monotonous. Coupled with rapid development of new technologies like steel framing, this method very soon lost out to other competing systems.

Fabric-formed floors

The birth of the idea can be traced back further in time. The use of engineered fabric as formwork is attributed to the invention by the German builder/ inventor Gustav Lilienthal (1849-1933). Lilienthal first trained as a mason, then an architect. He built a house, promoted the fabric formwork qualities and built 30 more during the 1890s; many of these included his innovations with fabric formwork. In 1899, he filed a patent for his invention of using fabric or even paper to create a suspended floor.

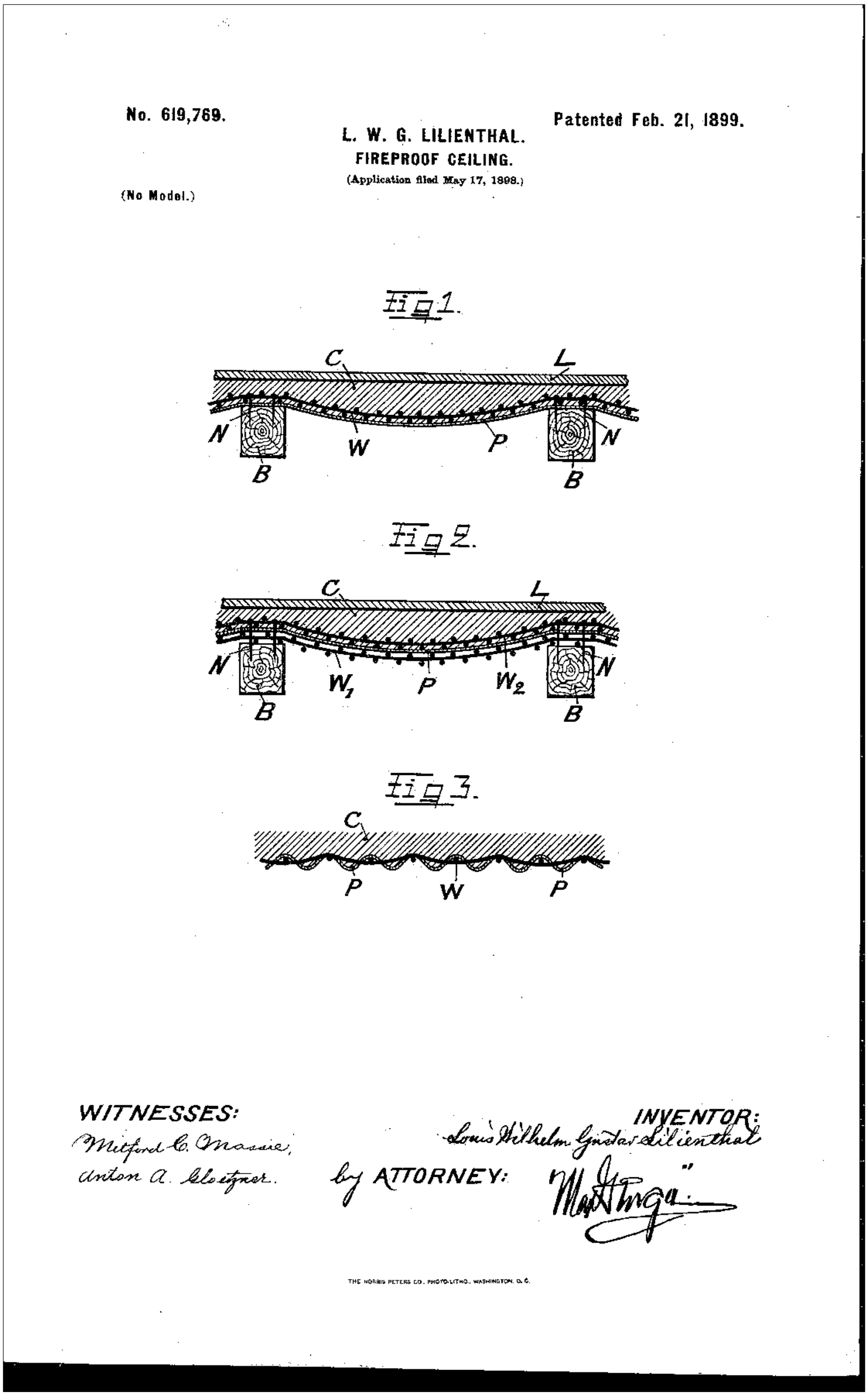


Fig 4.12. Patent drawings of the fabric formed floor from Lilienthal.

To form the floor, Lilienthal draped an impermeable fabric or paper over parallel beams. Then, above this, wire-netting was placed before concrete was poured on in layers. Lilienthal was mindful of the structural characteristics of this technology and observed how interaction of wiremesh, paper and wet concrete led to a surface similar to a soft cushion. An almost identical concept was filed for patent in India in 1937 which identified savings on centring and falsework material with cheap unskilled labour as a major advantage. It suggested other similar material such as hessian, cotton, wool, paper and even carpets of grass and leaves as possible draping membrane that could support the concrete. In 1971, a patent for a complete building utilising both belts and sheet material was also filed. This patent recognised construction economy and speculated a 20% saving (Veenendaal et al, 2010) due to parabolic shaping following bending moments of the span with the help of wire mesh as reinforcements. This proved that concerns on labour and formwork in concrete design are highly process-driven.

Although no photographic evidence is traceable, one can imagine a gentle undulation of concrete soffit on the underside of the floor. The internal space also benefits from advantages associated with thermal mass offered by the exposed concrete surfaces.

4.7.3 Flexible formwork as formwork for Pneumatic shells

Fig.4.13 1943 Wallace Neff's airform houses

Concrete can also be applied on flexible form work which is supported by air pressure. This very often gives rise in synclastic geometries exemplified by Bini and Monoliths shells.

Primarily, this principle was based on formwork supported by air. With a membrane tightly fastened to the ground, air is pumped to inflate the formwork. In 1942, the Californian architect Wallace Neff pioneered the use of inflatable domes as formwork for concrete bubble houses (Neff, 1941). The bubble houses, also known as *airforms*, were initially used for emergency war-time accommodation in the 1940s. Less known, Haim Heifetz built many shells in Israel during the 1960s using pvc-coated fabrics (Heifetz, H, 1972*)*. The variation and development on this principle has evolved over the years with varying success due to limitations of form freedom, always as versions of synclastic shells.

Dante Bini (Bini Shells)

> *"in 1964, Dante N Bini built the first hemispherical thin shell structure by pneumatically and automatically lifting all the necessary construction materials, which were distributed horizontally over a pneumatic form anchored to a circular ring beam, from ground level into a hemispherical dome. After the initial ground preparation was finished, that concrete thin shell structure was built in 60 minutes. "* www.binisystems.com

Once inflated, reinforcement bars are placed over formwork and secured with chairs. The sharp steel chairs could become problematic as they can depress or even puncture the inflated formwork. Concrete is then applied and sometimes sprayed on with shotcrete or gunnite. As one might imagine, it is difficult to affix reinforcement bars onto a smooth pneumatic membrane. However, the Bini system breathed new life into shell construction. Dante Bini and his son Nicolo continue to build shells this method today. The system claim that it can build concrete shells with a radius between 12 and 40 metres in approximately 60-120 minutes (www.binisystems.com).

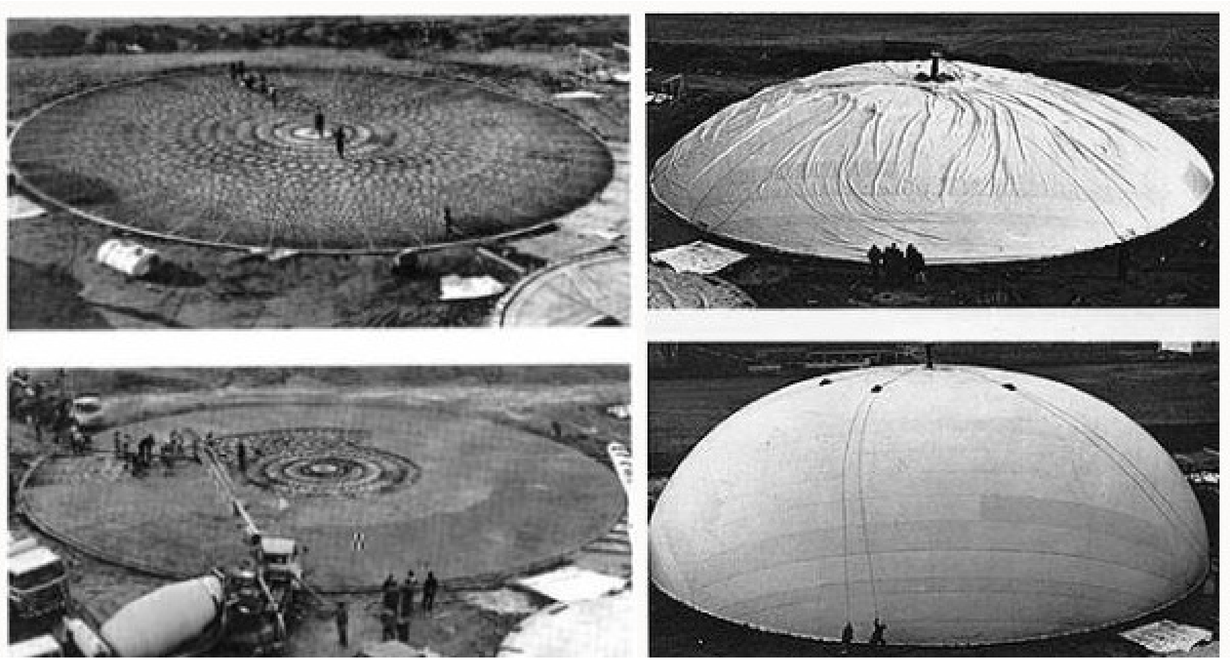


Fig 4.14 Inflatable fabric formwork being used to create large spanning structures however with limited geometrical variation. **http://ileklab.de/?p=239**

The advantages of building this way are associated with the cost and speed of construction. The spans of Bini shells are very attractive too. Unfortunately, being cheap and structurally efficient is not enough. Technology must also offer adaptability. Unfortunately, form opportunities offered by pneumatic fabric formwork are limited. Additionally, they are also difficult to adapt, modify or be repeated. As the concrete is applied on the upper side of the membrane, waterproofing and insulation have not been taken into account. Over 1000 'Bini-shells' had been constructed with this method by 1986 (Roessler and Bini, 1986)

David and Barry South (Monolithics Inc)

In the late 1970s and early 1980s, David and Barry South of Monolithics Inc. developed a system where polyurethane foam was sprayed onto the inside of an inflated fabric formwork. The foam provided stiffness and support from the inside. Shotcrete was then applied on the interior of the form and eventually formwork was either removed, reused or left in place. This system was frequently used in the US. The inventor claimed that spans in the range of 30-60m were common and spans up to 300m possible. The Texas based firm reportedly shipped 150 pneumatic forms in 2001 and has participated in the construction of shells in 48 states and in over 30 countries (Bechthold, 2009: p151).

Another method of using pneumatic formwork is to lay on the concrete while the formwork membrane was deflated. Before the concrete cures, it was inflated with special reinforcement patterns used to control the displacement and sliding of the bars while formwork was inflated (Bechthold, 2009: p151). South used the membrane as permanent formwork, or sacrificial formwork, providing a waterproof layer. Compared to the principles of Bini shells, Monolithics' method produced better structures that perform environmentally to exploit the thermal mass of the sprayed concrete on the shell underside.

Ball Houses Series by Heinz Isler

Interestingly and of note, Heinz Isler worked with this method of shell construction in his “Ball Houses” in the 1970s for earthquake resistant houses in Iran. They were made with sprayed gypsum/loam mixture or gypsum/cement mortar. He has also worked with the architect Michael Balz on the Balz House at Stetten auf den Fildern, near Stuttgart in 1980. The shell was constructed in 3 layers with internal concrete, foam insulation, then external grade concrete. It was noticeably difficult to place traditionally shaped furniture in the house and many had to be commissioned specially (Chilton, 2000: p128). This is project is illustrated in fig 4.15 below.

Fig 4.15. Balz House which used sprayed concrete for construction resulted in curved spaces which required bespoke furniture to be commissioned to fit into awkward spaces. www.anc-d.u-fukui.ac.jp

Pneumatic formwork was an exciting way of building shells. Unfortunately, this application was limited to dome shapes. Although shells were erected at great speed, the formwork repeated the same shapes bearing a monotonous result. With the exception of scale variation, in aesthetic terms, form expression was limited. Structurally, they also posed difficulties in allowing natural daylight to penetrate into the dark spaces as openings compromised the structural integrity.

Inflatable Concrete Canvas

More recently, concrete impregnated fabric was investigated by a British enterprise called *Concrete Canvas*. Also under market license, the company speculates new uses of pneumatic systems in a variety of systems including creating temporary accommodation by inflating a pre-stitched Concrete Canvas tent with a pre-attached door during crises of war. Once inflated, the cement impregnated concrete is hydrated and within 24 hours of curing, the rigidized temporary shelter can be used. Fabric thickness varies between 5 and 13mm and is presently used in ground engineering projects such as protection of ditches and canal linings.

Fig 4.16. Concrete Canvas's proposal means temporary accommodation can be created from an inflatable formwork in hours. (courtesy of Concrete Canvas Ltd)

Bechthold (2008: p152) described the innovative idea of using pneumatically formed concrete gridshells by Ing Zimmermann at the University of Kassel where a double-layered membrane was welded together to create a network of interconnected tubes. This system will be placed on site and fastened securely to the foundations strong enough to resist membrane uplift. Once sufficient negative pressure was achieved, the interconnected tubes are inflated and incrementally filled with the UHSFC (ultra-high strength fibre cement) eradicating the need for steel reinforcement. The membrane was then used as waterproofing and protection. This is a clever departure from the conventional way of making concrete shells. It also solved the problem of cladding and offered the opportunity to allow natural daylight to penetrate into the sheltered space.

Fig 4.17 Membrane Concrete Grid Shells invented by Ing Zimmermann. (copyright Ing Zimmermann)

4.7.4 Pre-cast elements with use of flexible mould. Tensioning the smaller sections and casting an in-situ topping.

Tensioning smaller sections and casting an in-situ topping. This method requires a changeable surface onto which concrete is applied to produce small sections of curved concrete. A larger curved surface can be formed when these smaller sections are assembled together. This idea was explored in the PhD research of Roel Schipper (2015) at TU Delft.

Fig 4.18 Roul Schipper from the TU Delft Faculty of Engineering and GeoSciences's PhD work entitled "Double-curved precast concrete elements: Research into technical viability of the flexible mould method" investigated the use of flexible mould to produce discrete sections of rigid panels with very specific curvatures. (copyright Schipper, H. R., & Janssen, B, 2011 and Schipper, H R, 2015)

Conceptually, curved surfaces can be divided into smaller discretisized panels. The use of actuators proposed by the Dutch engineer Schipper, 2015 could modify a rigid mould onto which a thin layer of concrete can be poured to produce discretised panels which can be joined together to create a continuously doubly-curved surface. Although the system achieved good results, it also raised issues around the interfaces between these panels and how they are connected or join up.

The difficulty of panelised sections of concrete is two-fold: firstly, that of accuracy (control and checking during fabrication process; and especially with the edge finishing) and secondly, continuation. The way each panel is pieced together requires a high degree of precision. Fig 4.18 illustrates these issues. Continuity in material will not be an issue if the system was non-structural. However, a structural system would require material continuity if it were to transfer forces efficiently to the ground when used as a shell.

4.8 Architectural Applications:

Although often used in civil engineering projects and marine scenarios, their applications in architecture is still at infancy. The rise in their use in recent years is also due to the invention of woven fabric coming down in price.

Again, these concrete formed elements and technology is still unfamiliar in architecture, especially when applied structurally as beams, trusses or walls. Their potential to be applied into the construction industry are currently being explored at various institutions in the UK and overseas. To date, few architectural projects have employed this technology aesthetically (ie as an architectural finish), The current success of fabric formwork application is attributed to the designer being the contractor or builder as this averts the scepticism of contractors (Veenendaal in West, 2016).

The 1980s and 1990s saw the spearheading of this use of fabric being experimented in Canada by Professor Mark West and the Japanese architect Kenzo Unno. West who trained as a builder and educated as an architect, developed these ideas with fabric formwork initially for column forms. Formwork was imagined for panels, walls, slabs, beams and thin shells, all using flat sheets of fabric. When filled with concrete, fabric formworks produced gravitationally expressive forms, sometimes eerily beautiful, sometimes organic and human-like. Not restricted to walls, fabric formwork saw guises of pre-cast columns and concrete slabs made using fabric formwork. These structures readily responded to gravity. Projects include a fabric-formed tilt-up wall system in Chungbuk, Korea (2010) and a system of fabric moulded canopy for a Women's Hospital with a series of double armed columns cast using fabric concrete (West and Araya, 2012). In Vermont in the United States, Sandy Lawton of ArroDesign has designed and bravely and successfully built wide outdoor concrete stairs using this construction methodology (Lawton and Miller-Johnson, 2012). Using this system, architecturally interesting features such as stair corbels were cast.

Some examples of projects that have used this technology is described below:

Hotel Tre Islas, Miguel Fisac, 1975

4.8.1 Miguel Fisac (1913-2006)

Fisac pushed the boundaries of ideas surrounding fabric formwork and expressed strong opinions about this. He questioned the borrowing of the wooden textures of timber formwork and this opinion can be seen in some of his projects where he rebelled against the principle of this aesthetic expression.

Fig 4.19 Fabric-formed concrete cladding panels installed for the façade of Hotel Islas Tres, Fuerteventura, 1975 (image copyright of Foundacion Miguel Fisac)

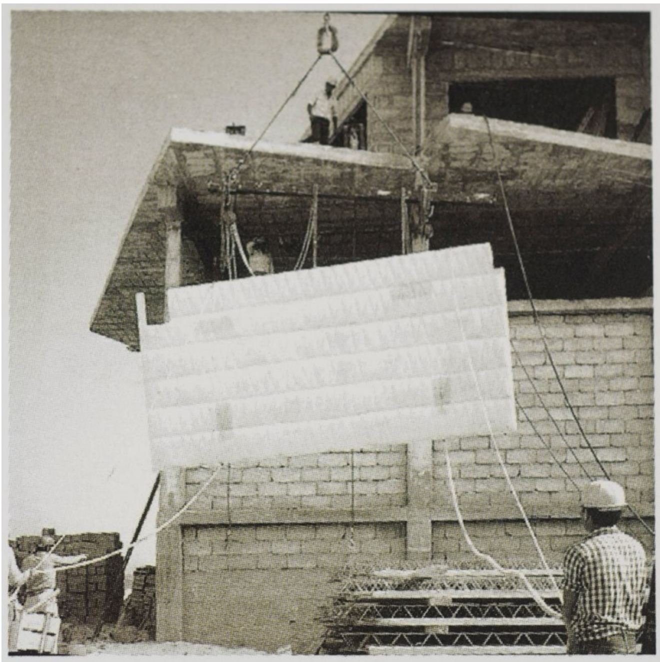


Fig 4.20 Fabric-formed concrete cladding panels craned and installed. Hotel Islas Tres, Fuerteventura, 1975 (image copyright of Foundacion Miguel Fisac)

Fisac challenged and reconsidered the qualities of concrete by using a smooth and flexible membrane hanging to produce panelised cladding. The result that the weight of this soft material gave to the concrete when poured is real and effective, taking on catenary forms that conformed to laws of gravity. Additionally, and more importantly, concrete takes on the texture of the fabric material in a tactile way. This method was employed in the Hotel Tres Islas and was used throughout the 1970s to great effect. Almost 2000 modules were used at the Teatro Municipal Miguel Fisac in Castilblanco de los Arroyos.

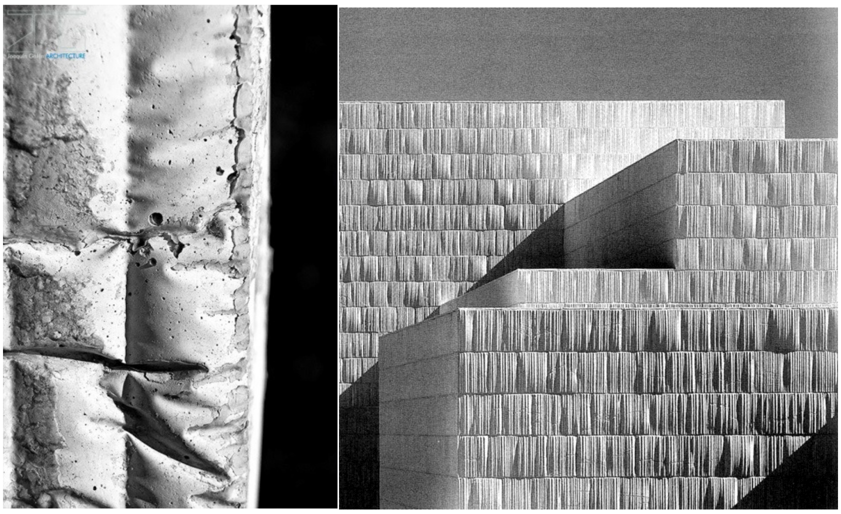


Fig 4.21 Teatro Municipal Miguel Fisac left: detail (architecturejoaquingalan.blogspot.co.uk), right: elevation (preciousandfregilethings.tumblr.com)

4.8.2 Hanil Visitor Centre and Residences in Chungbuk, South Korea, 2010 BCHO with Mark West

The fabric formed load bearing walls has been designed for the concrete factory to showcase design possibilities with concrete. They line the east façade of the building. These panels were pre-fabricated and then erected by tilting and pushing them upwards.

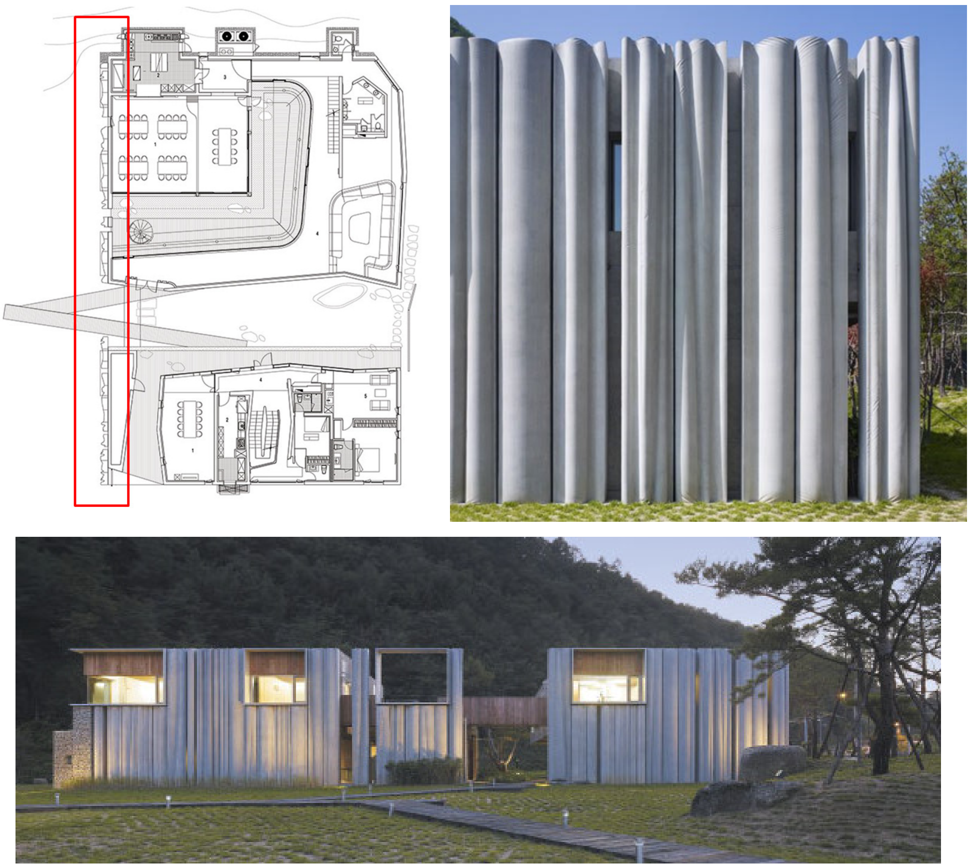


Fig 4.22 Fabric-formed tilt-up wall system in Chungbuk, Korea designed in collaboration with Mark West (© wooseop hwang)

4.8.3 Kenzo Unno

The Japanese architect Kenzo Unno has designed many residences using fabric formwork. In his application, he constructs the beautiful undulating loadbearing concrete walls exposing concrete cushioning to the interior environment to harness their thermal mass. He used this "frame-restraint method" which restraint the geo-textile fabric. As seen in the sectional material build up, the fabric on the right inflates once filled in with concrete to result in undulating curvatures. The formwork is restrained with "button holes" which connects both sides of the formwork build up.

Fig 4.23: Zero-waste formwork by Kenzo Unno and resulting wall in the “URC house with grass” in Edogawa-Ku, Tokyo, Japan (2003)

4.8.4 ArroDesign Sandy Lawton 2012

"Fabric formwork has given us the freedom to do complicated structural work in a very different way that's not complicated at all. That's the bigger advantage. There's a lot more flexibility with this system" Lawton said during an interview with Concrete décor. Rigid formwork can be complicated and labour intensive. Lawton used fabric formwork to create many structures including an outdoor staircase in Vermont, USA.

Fig 4.24 Fabric formed outdoor staircase constructed of concrete formwork in Vermont, USA (copyright Sandy Lawton, ArroDesign)

4.8.5 For a competition entry, ideas for concrete structures cast over fabric cable net formed structures were proposed for the design of a bridge-like nature crossing in Vail, Colorado United States in the shape of a concrete hy-par shell by the architects ZJA in Netherlands.

Fig. 4.25 Vail Wildlife Crossing, Colorado, 2012 (image copyright of ZJA architects).

4.9 International Research Attention

The ISOFF International Society of Flexible Formwork was founded in 2008 to promote the application of fabric formwork in architecture. Fabric formwork applications are also developed as a structural solution by academics researching in this field. Institutions such as The Centre of Architectural Structures and Technology (CAST) at University of Manitoba, Canada founded by Mark West, and also through the works at The University of Edinburgh (Remo Pedreschi), The University of East London (Alan Chandler) and researchers at the Danish Royal Academy of Fine Arts Copenhagen are exploring the aesthetics of these kinds of structures.

In Britain, the collaboration between Remo Pedreschi at Edinburgh University and Alan Chandler at the University of East London have seen the further extension of fabric formwork research. The collaboration of educational workshops inspired architecture students through intriguing dialogues between form, material, process and artefact. The structural engineer Daniel Lee also continues to investigate in this area of fabric formed concrete.

4.10 Relevant Projects

The following sections describe research and experimental activities where academics in both architecture and engineering carry out research in the form of research-informed teaching, some in the methodology of experiential construction and Flash research (Benjamin, 2012).

4.10.1 Wall ONE, Alan Chandler, UEL 2004

Chandler used construction workshops to open up tectonics and materiality discussions through a series of concrete construction workshops in his work as an educator. The One Wall was built to develop a philosophy of engagement between architectural teaching and practice, treating materials research and design as facets of one activity."(Chandler 2004).

Fig. 4.26 Wall One by Chandler et al. The pioneering Wall One was constructed at the University of East London in collaboration with CAST, University of Manitoba, University of Edinburgh. (copyright of Chandler, 2004).

4.10.2 Installation for Chelsea Flower Show, Chandler and Pedreschi, 2009

The installation of flowing walls was cast and installed with Chandler at UEL in 2009. 19 sections of concrete walls cast in fabric forms were constructed as interlocking wall like a three-dimensional jigsaw puzzle with the largest section measuring 2.5m by 0.75m.

To define the undulating geometry, plywood profiles were used, similar to ensure that the ends of the shells were uniform. In total, the panels covered an area of 21 square metres. The formwork was assembled and concrete cast by senior architectural students. The concrete used reclaimed sand and crushed concrete and recycled materials (Pedreschi and Chandler, 2017).

Fig 4.27 Fabric formed elements collaboratively between university of Edinburgh (Pedreschi) and university of East London (Chandler) as part of the annual Chelsea Flower Show 2010.

4.10.3 Defying Gravity- project at Edinburgh University

Students of architecture designed and built this structure at Edinburgh University under the leadership of Remo Pedreschi. For this project lasting 5 weeks, students of architecture experimented with the use of tensile membrane with the aim of achieving parabolic geometries without substantial rigid formwork. The shell was cast in two halves and required mechanical connections in the form of threaded elements to be cast at the top of the parabolic halves. This was a re-iterative process of learning from smaller scale mock-ups and testing. To achieve the final artefact, laser cut sections and edges were used to achieve a geometrical accuracy, imperative to connect the two halves together. Steel mesh and reinforcements were cast into the shell as structural precaution (from cracking) and for stiffening.

Fig 4.28 Defying Gravity 2008, A joint project by architecture students at University of Edinburgh explored the construction to scale in two parts. Students collaborated within a 5 week period, liken to the format of Flash Research (courtesy Edinburgh University)

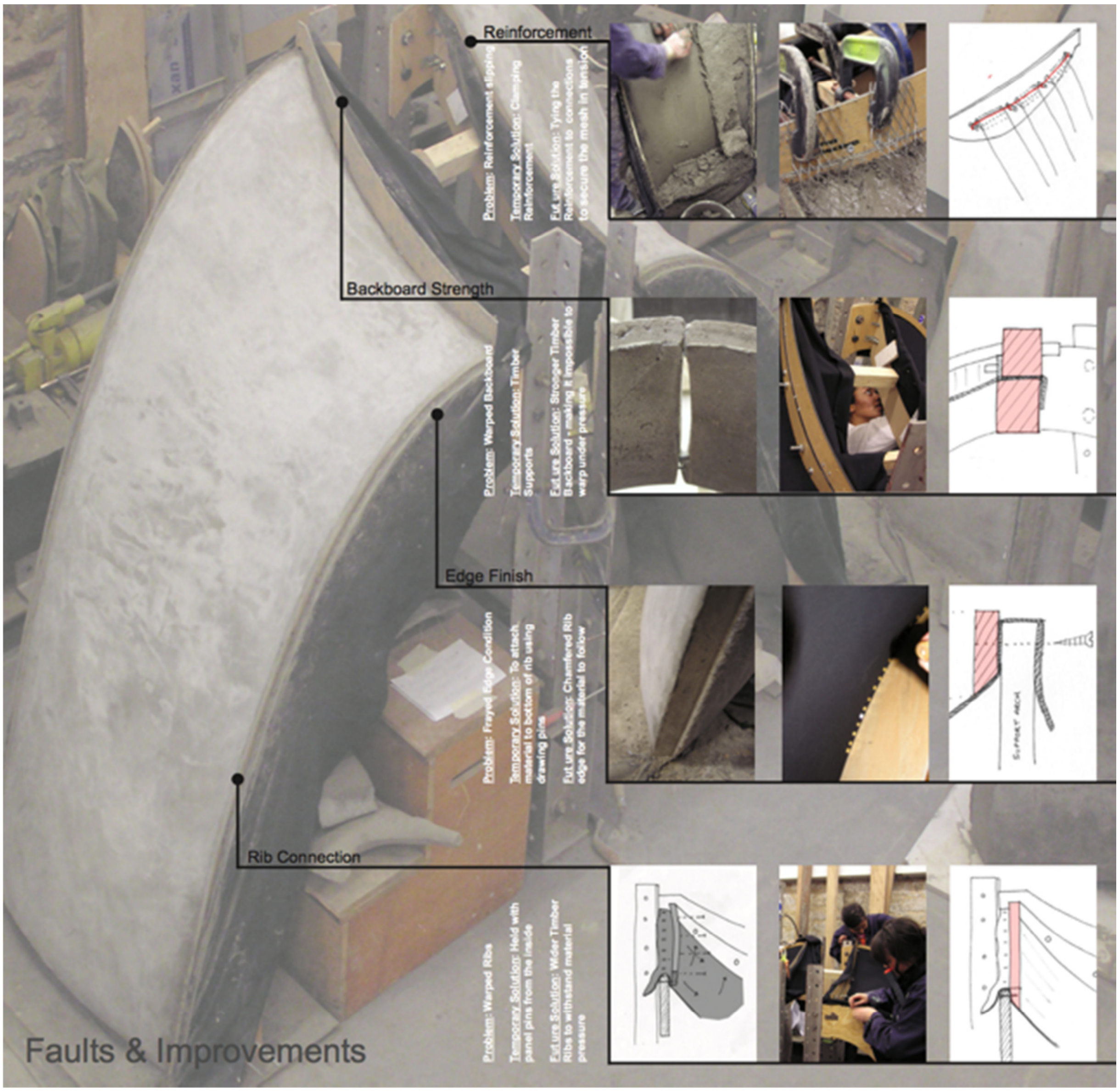


Fig 4.29 Defying Gravity 2008. (courtesy Edinburgh University)

4.10.4 Hy-par, Edinburgh University, 2011

Another project under tutorship from Remo Pedreschi in the form of construction is a shell constructed using fabric as formwork. The flash research saw the refinement of the edges which incorporated tension cables to stabilise the shell standing on two side abutments. The exercise also saw the use of reinforcements and the casting of connection holes for passing stabilising tension cables.

Fig 4.30 In 2012, for one of the year-long construction projects, students at Edinburgh University constructed a hyperbolic paraboloid using fabric as formwork. This was stretched at the high points and at their footings. (images courtesy of https://ghaui.wordpress.com/)

4.10.5 For his PhD entitled "Study of Construction Methodology and Structural Behaviour of Fabric-formed Form-efficient Reinforced Concrete Beam", Daniel Lee constructed 11 concrete beams. This was driven by the quest to refine form-active beams, with a strong sense of aesthetic and material economy.

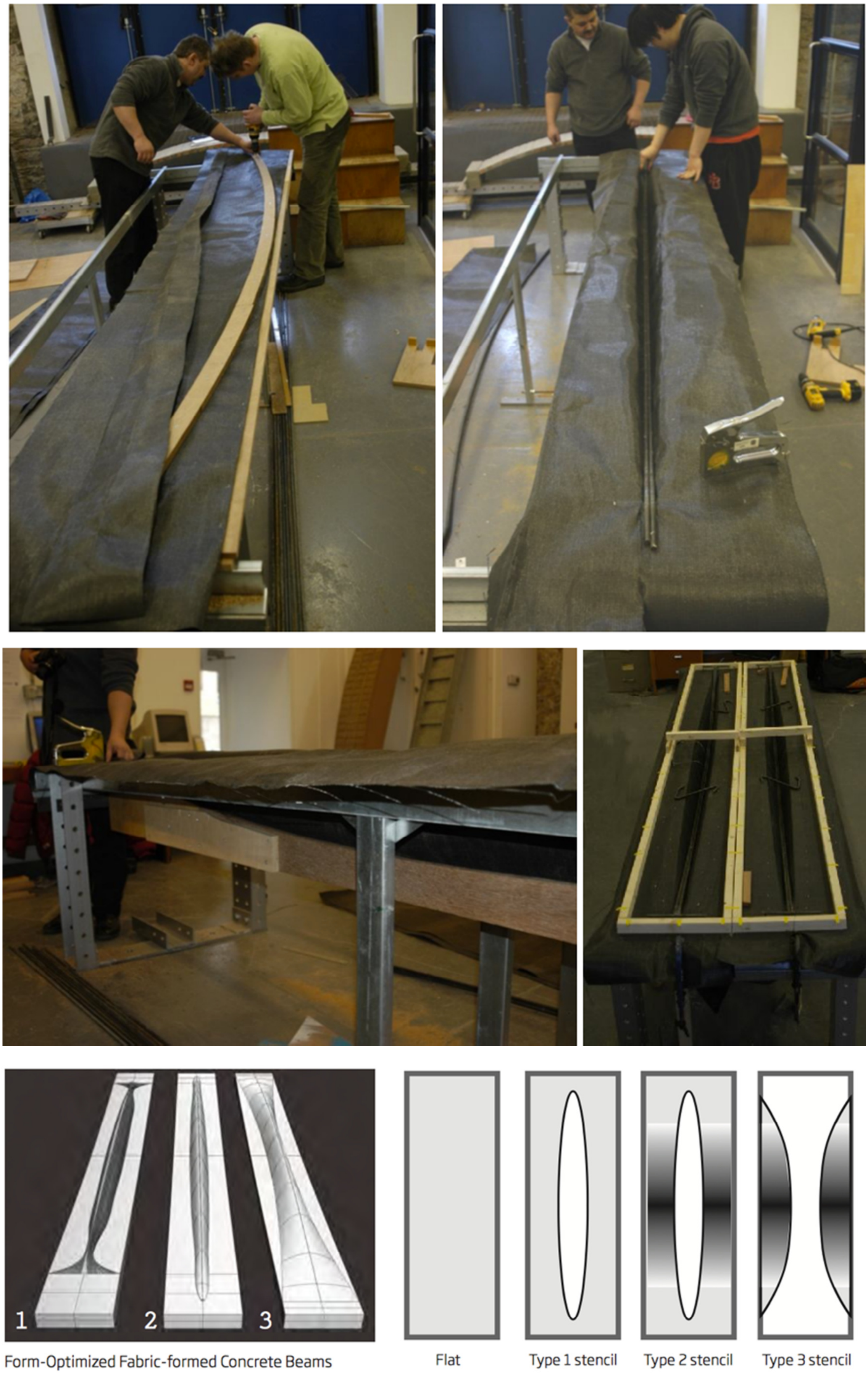


Fig 4.31 Casting of 11 fabric formed concrete beams carried out by Daniel Lee (images courtesy of Daniel Lee, 2011).

4.10.6 PERFORATED CURVED S/ WALL

In Copenhagen, the architect Anne-Mette Manelius led numerous student workshops as part of her 2012 PhD which questioned the tectonic expression of concrete through fabric formed concrete via her PhD entitled Investigations into Formwork Tectonics and Stereogeneity. Her work described an extensive experimentations and a collection of techniques that vocabularised this technology. The study discussed the important roles of various elements in the system of fabric forming and includes the relevant elements of the frame/ rig and form tie/ impactos.

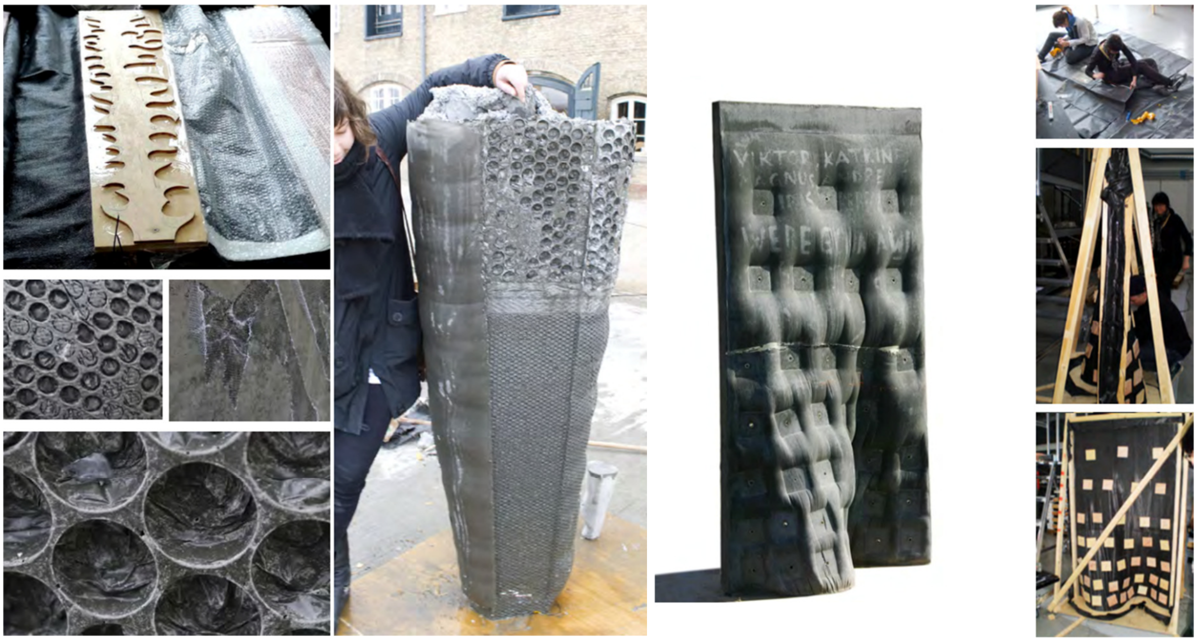


Fig 4.32 left: Hexagonal Cone and right: Clamp Wall. (courtesy of Manelius, 2012)

Frame/ rig

Her research recognised the frame as a "textile suspension device" which "entails the conceptually linked opposition of releasing form. The frame restrains and supports the fabric.

This description of frame is highly relevant to the hypothesis in that the deployed gridshell performs the function of the frame as it is from the gridshell where from fabric is supported or suspended. Some of the construction showed the importance of the frame to restrain at the top and bottom edges. However, their important (but temporary) presence is not wholly expressed in the eventual output. The Clamp Wall (fig 4.32) and the perforated curved S/Wall (fig. 4.33) shows the use of the frame in suspending fabric formwork in space. Restrained using form ties and impactos, the wall was cast. However, after all formwork was removed, the presence of the frame was lost.

In this way, the gridshell as frame is more intrinsic to the resultant cast as the structural shape of the resultant concrete shape totally depended on the shape of the gridshell frame to determine the shape and structural capacity as shells.

Form tie and impactos

In traditional plywood concrete shuttering, form ties/ rods linked two sides of the formwork together but maintained a space for the concrete to flow into. To provide restraints to fabric formwork systems, the use of form-ties and impactos can be used to connect the two sides of the system together. In fabric formwork, these restraints are important elements as they do not just connect the 2 sides together, but are instrumental in creating undulations in concrete forms. It is through this hydrostatic interaction between concrete and fabric which imparts the form characteristics of fabric formed concrete i.e. bulbous cushioned concrete panels. Form ties in fabric forming systems can be soft and flexible (e.g. string) or rigid (e.g. a rod).

Impactos, like form ties, clamp both sides of the system together. Depending on how much they are clamped, they offer the opportunity to create different effects on the output. As such, the process of designing fabric formworks is highly reiterative. It is through experimentation that the potential effects can be achieved or designed.

Impactos can also be flat plates that sandwich the 2 fabric layers together. If they are clamped very tightly, concrete poured into the forms flows around them and form openings when concrete is stripped.

If the impactos are clamped loosely together i.e. with an actual tension connection in between (eg string or a form tie rod), concrete can flow around the spaces and as the form fills up, impactos imprints express their presence (see Wall One by Chandler and Pedreschi, 2007 and Clamp Wall by Manelius discussed earlier). Therefore, impactos are opportunities to create openings on a fabric formwork surface. The projects by Manelius and her students chosen to demonstrate fabric formwork ideas relevant to this research study.

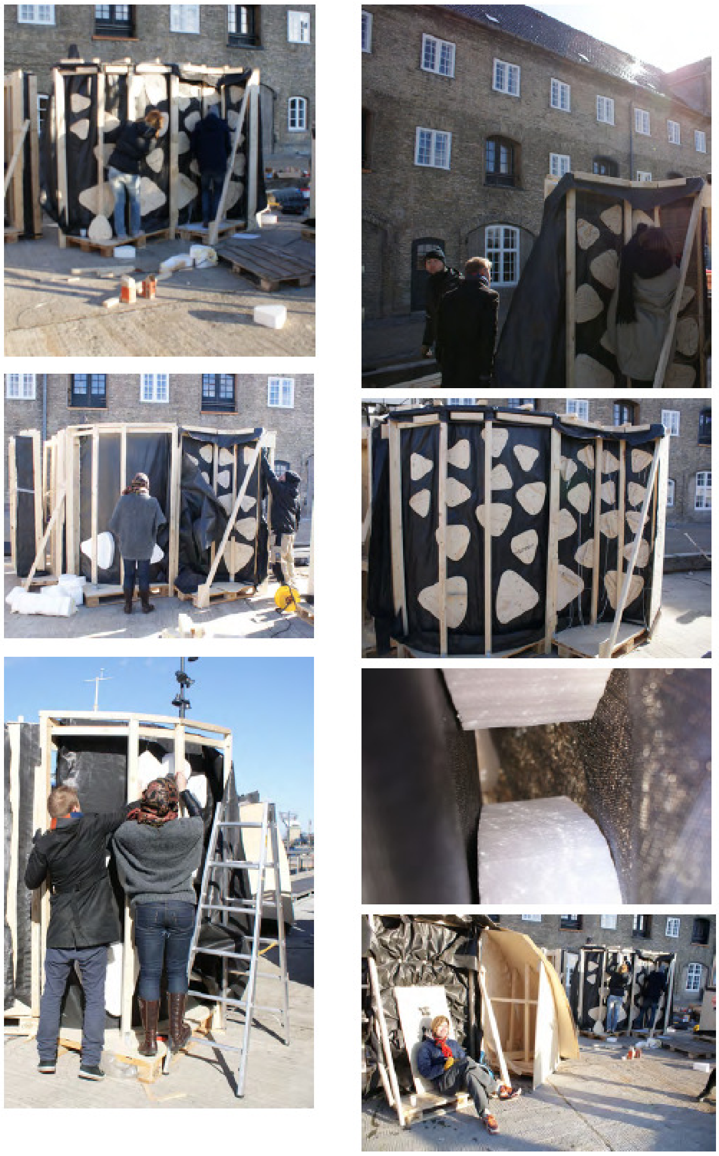


Fig 4.33 Perforated Curved S/ Wall construction sequence (copyright of Manelius, 2012)

This project is picked out to illustrate the effective use of impactos on the design and how these restraining features can help to create openings in a concrete wall.

4.10.7 Tension Cable-Stayed formwork (ETH)

The idea of casting concrete using tension cable-stayed elements was researched by Dr D Veenendaal, at the Block Research Group at ETH, Switzerland. This technology is planned to be used for the HiLo Nest project to be built in Dübendorf, Switzerland, in 2016 (Veenendaal, et al 2015, Veenendaal and Block, 2014). The prototype displays a strong stereogeneous approach and displays cushioning on the underside of the shell. Although the technology is different, this hy-par shell resembled the shell constructed by Pedreschi and his senior students at Edinburgh University in 2011. Both hy-pars showed that the same architectural concept/ form could be achieved by employing different technologies and methods. An alternative to creating this hy-par structure may be to use timber boarding as formwork for concrete to be cast onto, as Felix Candela would.

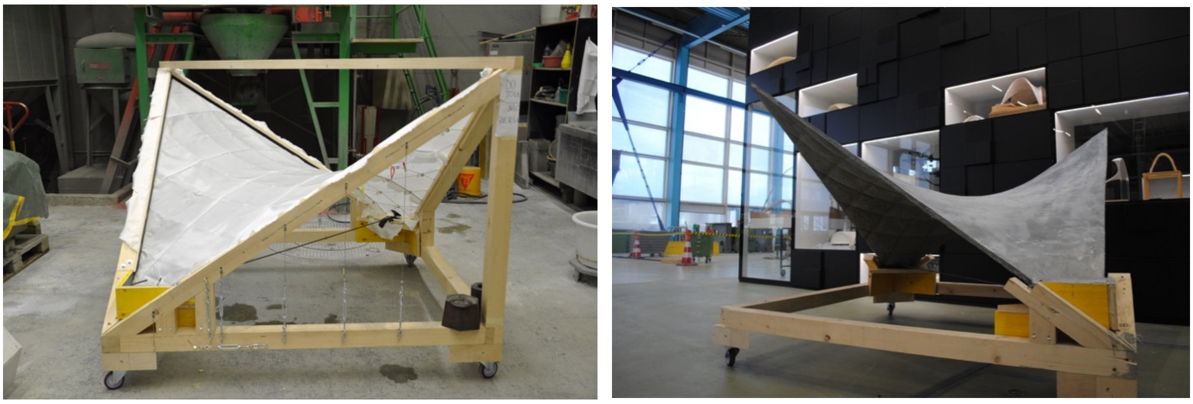


Fig 4.34 Model of the use of cable stayed fabric formed hy-par shell prototype. Tensile cable net formwork (Copyright: Diederik Veenendaal)

The use of fabric woven formwork material will also require consideration in the following areas:

4.11 Technical issues:

4.11.1 Woven material - adhesion, stitching and textures

Fabric used in fabric forming could affect the way the concrete shell is expressed. These include mechanical properties of elasticity and texturing.

Fabric can be woven or non-woven however woven fabrics are preferred due to their availability, low cost, high strength and positive effect on surface finish High stiffness fabrics can withstand large pre-stress forces and large fluid pressures (Orr, J., Darby, A., Ibell, T., & Evernden, M. (2013). New textile technologies and stitching machineries have allowed woven shells to be stitched together in the factory. However, plastic materials could be welded on site as an option.

4.11.2 Concrete mix

Fabric allows water and air to escape from the concrete to ensure high quality and uniform finish, also reducing the occurrence of blowholes and other imperfections. With the egress of air and water, this allows a desirable rich cement surface layer (Orr, J., Darby, A., Ibell, T., & Evernden, M., 2013).

4.11.3 Reinforcement:

Steel reinforcement bars and mesh may be embedded within weaker areas or areas with increased curvatures, glass reinforced polymer re-bars, reinforced carbon fibre cages.

4.12 Conclusion

As one of the three constituent technologies in this research work, fabric offers a potential to solve the problem of enclosing a three-dimensional surface. The examples show how fabric does not just conform to curves under the weight of wet concrete to produce structurally efficient shapes but could produce unusual catenary forms imprinting the textures of the supporting fabric Together with economy and the opportunity to create desirable finishes, they offer the designer a way to envelop a doubly-curved gridshell framework. Fabric formwork offers the opportunity for air to escape to produce fine finishes of concrete as well.

The ambivalence of this architectural application can be traced to the unfamiliarity of this system by designers as an aversion to risks associated with a relatively new way of building using fabric formworks but with these advantages, the use of fabric formwork is an interesting idea to integrate and to pursue to make this system work.

The following chapter will discuss the background to the third and last component of technology: the deployable actively bent gridshell as a framework upon which fabric formwork is supported for concrete shell casting.

Timber Gridshells Workshop, Sheffield Hallam University, 2011 (courtesy id8 Photography)

PART 2 THE CONFLUENCE OF TECHNOLOGY

Chapter 5

DEPLOYABLE AND ACTIVELY-BENT GRIDSHELLS

Chapter 5
Deployable and Actively-Bent Gridshells

The gridshells employed in this thesis are both deployable and actively-bent, belonging to a particular family of gridshell structures. Much of this chapter is informed by research conducted in preparing for the book Timber Gridshells: Architecture, Structure and Craft published by Routledge co-written by the author. The book charts the development of gridshells in timber realised in the last six decades.

5.1 Introduction

In 1974, the Institute of lightweight structures at the University of Stuttgart founded by Frei Otto published a special edition of IL10 dedicated to gridshells. In this, Hennicke and Shaur, provided a detailed technical definition of a gridshell:

> *"The grid shell is a spatially curved framework of rods and rigid joints. The rod elements form a planar grid with rectangular meshes and constant spacing between the knots [nodes]. The form of a grid shell is determined by inverting the form of a flexible hanging net. To invert the catenary so that it becomes the thrust line of an arch free of moments is an idealisation. Analogously, inverting the form of a hanging net yields the support surface of a grid shell free of moments."*

The description not only described what the gridshell was, but was very specific with the method of efficient form-finding. This was described by the use of hanging chains used in many early form-finding of gridshells in the 1970's (Liddell and Happold 1976, Chilton and Tang 2017). Since then, this prescriptive definition has changed dramatically due to advancement in analytical and fabrication technology. In today's digital age, to form-find by building a hanging chain model must appear curious and esoteric. During the design of the Weald and Downland gridshell in 2000, project architect Steven Johnson from Studio Cullinan, London revised this definition, providing a simpler definition:

> *"A shell is a natural, extremely strong structure.*
> *A gridshell is essentially a shell with holes,*
> *but with its structure concentrated into strips".* (Johnson, 2000).

Very interestingly, the latter description omitted form-finding or construction method. Both definitions maintain key concerns on shape/ form and structural behaviour. The question of "how to construct" was therefore separated from the design / form-finding process. Developed by Frei Otto at the University of Stuttgart, with the Essen gridshell constructed in 1962 as a pioneering project, the method of cross-lapping timber laths and connected with articulated joints was widely recognised as an inspiring method of constructing doubly curving shells. This method relied on the ability of cross-lapped grid-mat to slide and deform.

5.2 The Prime Challenges of Gridshells

Despite being useful, this system of construction has two prime challenges: accuracy and effective surfacing.

5.2.1 Accuracy of Deployability.

Deformation is difficult to control. In fact, Mannheim Multihalle (1976) initially dropped by 200mm between temporary supports during construction (Liddell and Happold, 1975). However, its deployable nature meant that it was subsequently adjusted to an acceptable tolerance of +/- 50mm (Happold and Liddell, 1975). The Weald and Downland gridshell also experienced a deviation of +/- 50 mm over a 15 m span and height of 8.5m. (Harris et al, 2003). However, the flexible nature of the construction method and material meant that a deployed gridshell could be adjusted to the desired shape with designed curvatures. This changeable nature of the construction is its advantage, and disadvantage simultaneously.

5.2.2 Surfacing a Gridshell

Since the early 1970s, at the infancy of digital form analysis and fabrication, surfacing doubly-curved structures has always been a challenge. This issue was experienced by gridshells. To form a three dimensional envelope/ surface from two-dimensional surfaces with sufficient airtightness is difficult to achieve. Membranes (Mannheim Multihalle), standing seam rooves (Savill Garden Gridshell) and glass (Chiddingstone Castle gridshell) has been used, but with limited success.

Early gridshell student workshop studies devised at Sheffield form pedagogical exercises in form that did not consider enclosure or permanence.

As computer technology advanced, gridshells can now be constructed by assembling pre-fabricated curved and sometimes doubly-curved sections could be made easily and accurately by computerised milling machines. The accuracy of the structure is strictly determined by the relationship to the type of covering (whether it is a tensile membrane) or concrete or by the highly mechanised method of construction. These relationships are exemplified by recent projects such as The Pompidou Metz Roof (2010) by Shigeru Ban and ARUPs with a gridshell construction tolerance of 4mm over the length of 20m (Dobele, 2017). This accuracy has a bearing on the tensile membrane covering as large variation results in structurally undesirable wrinkling in the fabric itself.

Fig 5.1 Timber sections of Pompidou Metz showing very small deviations in dimensions (credit Tobias Dobele Holzbau Amann.de).

These projects are made possible by the use of over-sized glulam timber sections derived digitally and cut to fit in complex 3 dimensionally curved geometries (Chilton and Tang 2017). Therefore, these types of gridshells were possible without deformation in the first place to form accurate results. Deflection is minimised and the final “artefact” was precise to their designed geometry.

5.3 Gridshells: Actively-Bent vs Rigid

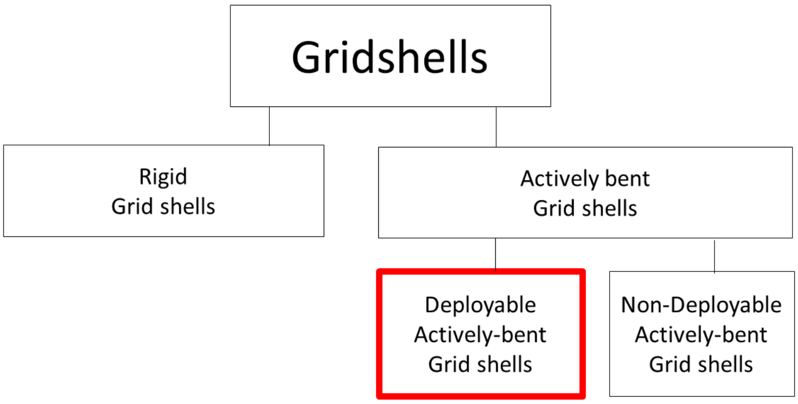


Fig 5.2 The Classification of gridshells

In the contemporary context of construction technology, gridshells can be classified into two categories according to their construction method namely the deployed/ actively-bent gridshell and the rigid gridshell.

5.3.1 Rigid Gridshell

The first gridshell category is rigidized by fastening discrete straight members or bespoke pre-curved and/ or rigid two-dimensionally curved sections together to form a three-dimensional structure. In recent times, this has been made possible by powerful CAD/ CAM processes and digital fabrication. Some examples of these include the Pompidou Metz (2010) as discussed earlier in France and Haesley Nine Bridges Golf course clubhouse (2010) in Korea, also by Shigeru Ban, as well as smaller pavilions such as the marine plywood gridshell (2013) designed for Singapore University of Technology and Design (SUTD) as well as The Kreod pavilion (2014) by Chun Qing Li of KREOD Architecture, London all of which used robotic routers where timber planks are milled to millimetre precision.

Fig 5.3 Rigid Gridshells: left: KREOD Pavilion designed by KREOD, London in 2012 was constructed from an assembly of rigid sections fastened together whilst the Haesley Nine Bridges project (right) by Shigeru Ban was craned to position in sections. (credit KREOD and HolzAmman)

5.3.2 Deployed/ actively-bent gridshell

This category of gridshells consists of deployable/actively bent gridshells which is also known as strained gridshell (Adriaenssens, Block, Veenendaal and Williams, 2014). Deployable and actively-bent gridshells are built by first fabricating a cross-latticing grid mat with long flexible members. These laths were then cross-laid with rotational joints which enable the resultant mat to deform through active bending to form three-dimensional shapes. This shape is then triangulated/ braced to rigidify the structure to induce in-plane stiffness. The early method of constructing engineered gridshells was pioneered by Frei Otto at Essen in 1962 (Hennicke and Shaur, 1974). The discrepancy brought about further constructional challenges of safety and practicalities in deforming a heavy gridmat from the ground and raising it to a high level with precarious temporary supports.

Fig 5.4 Manheim Multihalle is aexample of the actively-bent gridshell. (Gabriel Tang)

Fig 5.5 A flat gridmat at Sheffield Hallam University is in the process of being bent into a three dimensional shell. (Gabriel Tang)

To deploy, mats are initially constructed by arranging laths in two layers at right angle to the other. The loose intersecting joints allowed the square grids to change from squares into lenticular grids. Additionally, bracing elements either in laths, tensile cables or rigid panels (Hernandez and Gengnagel, 2014) can be used to restrain the shell and prevent it from returning to the flat mat.

Visibly, deformations must occur to define space and create three-dimensional doubly-curved forms. This deployability is useful for the designer to understand the material behaviour as it offers an intuitive way of working with shapes and materials. The concept is illustrated and explained in fig. 5.6 below.

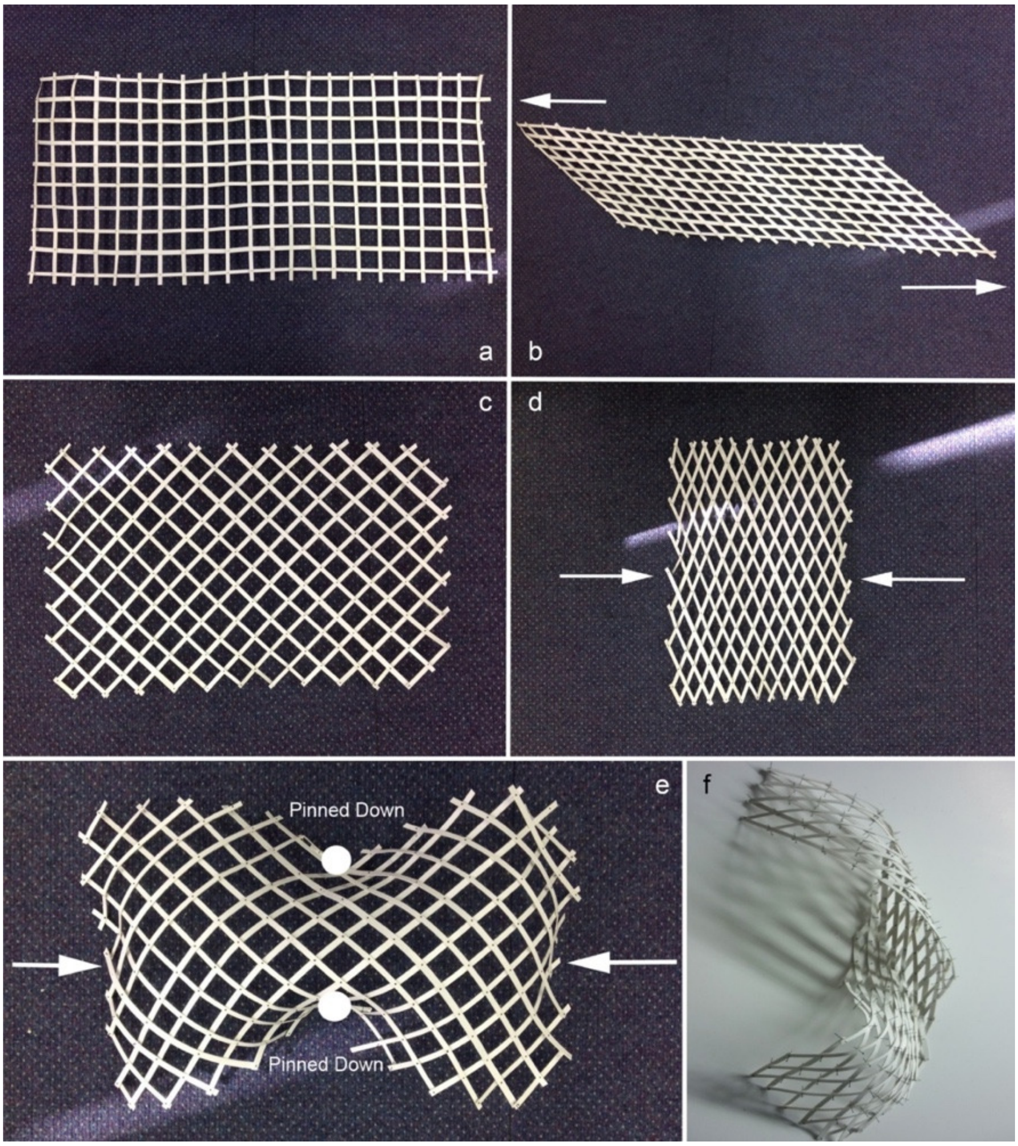


Fig 5.6 – Demonstrating the principles of deployability. (Abstracted from Tang, 2013)
a) and b) with a grid pattern perpendicular to the mat edges, upon application of forces indicated as arrows, the resultant has sharp corners at the ends and a resultant shape that could pose usability issues.
c) and d) with a grid pattern at 45 degree to the grid edge, the mat collapses to form a compressed mat without sharp corners when forces are applied, maintaining a rectangular proportion which is much more useable.
e) and f) By restraining some points of the mat and when forces are applied, illustrated by arrows, the actively-bent grid-mat deforms three-dimensionally to form shells. These gridshells can then be stabilized by the introduction of bracing elements to triangulate the structure.

5.4 A brief overview of seminal deployable and actively-bent gridshell

A gridshell is a form of "surface structure" (Angere, 1961).

The 1970s saw extensive gridshell experimentation and building activities, culminating in the construction of the actively-bent timber gridshell roof for Multihalle at Mannheim, Germany designed by architects Carlfried Mutschler and Partners and engineered by Frei Otto (Liddell and Happold

1976). The timber gridshell roof is the largest one built by far in the history of timber gridshells with a roof surface covering an area of 9,500 sqm and which spanned 60m.

After this period, gridshell activities diminished as alternative wide-spanning structural framing systems in steel and timber were preferred. Few gridshell structures were built in the 1980s and 1990s but less renowned as Mannheim Multihalle completed in 1976. For instance, the Nara Silk Road timber gridshell in Japan and the bamboo gridshell structures at Fukuoka were obscure and not very well-publicised at all (Chilton and Tang, 2017).

It was not until the early 2000 that saw the completion of the Weald and Downland gridshell (2002) in Sussex, England designed by Edward Cullinan architects (now Studio Cullinan) re-awakening an architectural interests in gridshells.

Deployable gridshell experimentations started in the 1960s with Frei Otto founding the Institute of Lightweight Structures. In 1962, a timber gridshell structure measuring 15m x 15m was built for the German Building Exhibition in Essen. Spectacularly, this deployability was harnessed in the construction of the German Pavilion in the 1967 Montreal World Expo. The structure was fabricated and assembled in Germany, before being collapsed, much like a wooden garden trellis, and transported to Montreal. In Canada, it was suspended under a cable-net structure to form a roof canopy to the pavilion vestibule. Re-deployed and re-erected, the timber gridshell measured 365 sqm and was built from 151 pieces of solid hemlock pine laths dimensioning 42mm x 28mm in cross-section and arranged in a 500mm by 500mm grid. Demonstrating this idea of portability to great effect, the design was the first engineered and constructed example of engineered transportability, re-configurability and deployability.

The effects of deployability were vastly improved through an understanding of design process at the Mannheim Multihalle, Germany 1976. This was described in the seminal paper by Liddell and Happold (1975). In Chapter 2 of Chilton and Tang (2017), a detailed description of the design and construction of the Multihalle is presented with particular emphasis on the benefits of deployability in gridshell construction used at an unprecedented scale. Very interestingly, problems experienced during construction acted as the impetus for further development and improvements in gridshell construction methods. Practical issues such as a surface/ coating material, fire treatment and methods of membrane sealing of a three-dimensional surface remained unresolved issues.

The completion of The Weald and Downland gridshell recaptured this interest in 2002. The flat deployable timber gridmat was supported by adjustable PERI scaffolding at high level and dropped by gravity into its final position (Harris and Kelly 2002; Kelly, Harris and Dickson 2002; Harris, et al, 2003). Again, the deployable nature was used in the construction of the 2005 Savill Garden gridshell designed by Glenn Howells Architects for the Royal Landscape at Windsor Great Park. These three deployable gridshells will be elaborated in more detail in the following chapter section.

5.4.1 Notable projects (Permanent)

5.4.1.1 Mannheim Multihalle, Mannheim, Germany 1976


Fig. 5.7 Mannheim gridshell, Mannheim Germany 1976 (Gabriel Tang)

In the 1970s, Frei Otto and Ewald Bubner of Atelier Warmbronn, worked with the architects Carlfried Mutschler and Partner, Mannheim (Joachim Langner, Dieter Wessa and Winfried Langner) and Structures 3 group at engineers Ove Arup & Partners, London (with Ian Liddell and Ted Happold) on the largest timber gridshell structure ever to be built. Completed in 1976, it was designed for the National German flower show as a temporary structure. The timber gridshell remains standing today although it suffers from structural creep with the shell dropping gradually over the last decades. Some parts of the structure are propped up by timber posts during a visit in 2009. The roof spans up to 60m and the restaurant area, 50m. The heights of the hall and the restaurant rise to heights of 20m and 18m respectively.

The actively bent gridshell was constructed by creating a double layer intersecting hemlock pine timbers profiles measuring 42mm x 35mm, and 42mm x 28mm for the vestibule space. Each node of the double layer gridshell was screw-bolted with slots in the timber laths to allow them to slide and rotate during the erection process (fig. 5.10b). This enabled the gridmat to deploy and deform from a two-dimensional gridmat into a three dimensional shape. The 500mm square gridmat was then stiffened with twin 6 mm diameter, 19-strand steel wire ties installed at 4.5m centres each way (Happold and Liddell, 1975). The construction process involved fork lift trucks with spreaders pushing flat gridmat to produce a double curved shell deemed unsafe by today's standards. As the shell reached new heights, scaffolding sections were added to push the mat up further until it reached its design heights.

5.4.1.2 Weald and Downland Open Air Museum Gridshell, Singleton, England 2002

Fig 5.8, Jerwood Gridshell, Weald and Downland Open Air Museum, Chichester UK. Cullinan Studio (Edward Cullinan Architects) 2002 (credit Gabriel Tang)

The triple bulb shell measures 50m in length. In section, it rises to a height of 9.5m falling to 7.35m at the valleys. On plan, The Weald and Downland gridshell narrows to 12.5m across and widens out to 16m. The gridmat was constructed by a double layer of Normandy oak timbers 50mm x 35mm profile section with a combination of 1m or 500mm square grids. The timbers laths were finger-jointed off site, then scarf-jointed manually on site to form laths measuring up to 50m.

Fig 5.9, The timber gridshell relaxes over time from a flat mat at high level to create a triple-bulb Jerwood Gridshell at The Weald and Downland Open Air Museum, Chichester UK. (credit Cullinan Studio 2002).

Fig 5.10 (left), Clamp joints at Jerwood gridshell (courtesy Studio Cullinan) is designed to prevent severance of timber fibres made when slotted holes were drilled in the timbers of Mannheim Multihalle (right). (credit Gabriel Tang)

Improvements learning from lessons of Mannheim Multihalle gridshell were exercised in this gridshell. Firstly, the laths were clamped, instead of drilled through, eradicating the need to remove excessive lath material which would weaken them as was done to the timber laths of Mannheim Multihalle which led to fracturing cases. Secondly, the construction method was improved with “dropping” of gridmat from a high level through the use of adjustable PERI scaffolding improve safety. Instead of pushing the gridmat upwards precariously from ground level, the gridmat was allowed to be dropped and deformed over a period of six months from a high level (Harris et al, 2003, Chilton and Tang, 2017). Although slower in process terms, and requiring a more careful manipulation of timbers, the structural capability of timber was respected, requiring and developing the skills of the timber craftsperson all at the same time.

5.4.1.3 Savill Gridshell, Windsor, England, 2005

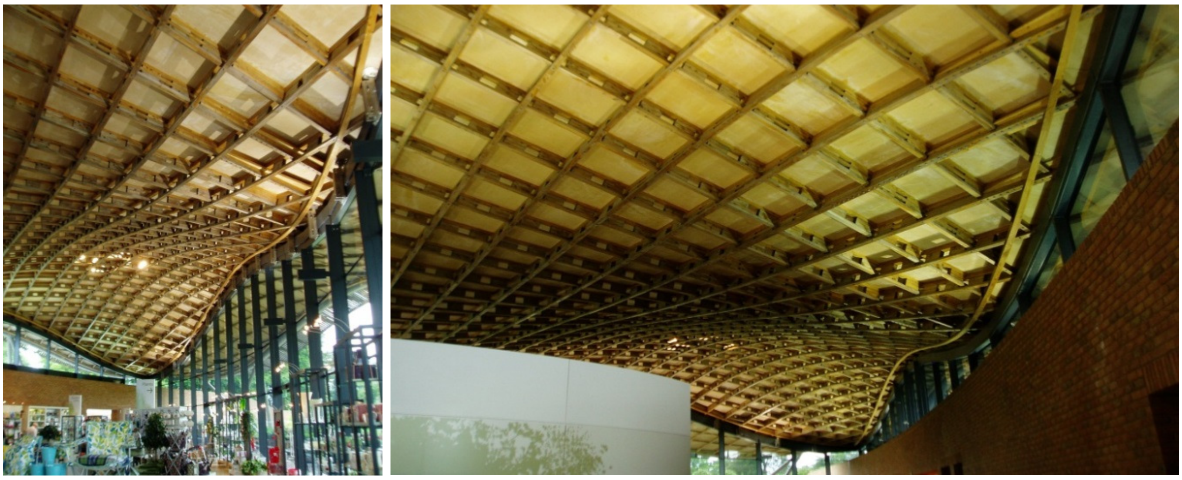


Fig 5.11. Savill Garden Gridshell, Windsor Great Park, Windsor Glenn Howells Architects 2005

Designed by Glenn Howells Architects in collaboration with Buro Happold, the shallow triple-bulbed Savill Garden gridshell measures 90m long and 25m wide (Harris et al, 2008, p28). It formed the entrance gateway to the Royal Landscape at Windsor, England. Again, the gridshell roof was formed out of a double layer locally harvested larch measuring 80mm x 50mm in cross section with 1m x 1m square grid. Once again, adjustable PERI scaffolding towers were used in a "drop down" forming process similar to the Weald and Downland gridshell. One of the distinctive features is the presence of a 400mm diameter tubular steel ring beam that collected the lateral hoop forces of the shallow gridshell.

The circular steel beam was raised on quadruple steel legs. Lateral bracing was provided by a double skin of plywood exposed on the interior of the visitor centre within which it encloses (Chilton and Tang, 2017).

Fig 5.12. One of the quadruple set of steel legs that support the 400 diameter ring beam restraining hoop forces of the gridshell roof. Savill Garden Gridshell, Windsor Great Park, Windsor Glenn Howells Architects 2005 (Gabriel Tang)

5.4.2 Seminal projects (temporary)

5.4.2.1 Japan Pavilion, Hannover, Germany (not re-erected but was temporary)

This project was designed by Shigeru Ban Architects as the National Japan Pavilion for Expo 2000. The gridshell measured 72m long, 35m at the widest and rose to a height of 15.5m enclosing an area of 3,600 m2. It was constructed of paper tubes 120mm in diameter, 22mm thick and 20m long bent to shape. This project was widely regarded the precursor of the “drop down” method as employed by Downland and Savill Gridshell. Seen in the photographs below, PERI scaffolding enabled the paper tubes to be dropped into shape by gravity. This concept was subsequently employed in later projects of the Weald and Downland (2002) and Savill gridshell (2005).

Fig 5.13 The Japan Pavilion at Hannover in the year 2000 made use of paper tubes lowered by gravity to form a triple bulb shape.

5.4.2.2. Solidays Pavilion , Paris, France, 2011

Fig 5.14 Using cranes, the GFRP gridshell was erected for the Solidays festival in 2011.

The project was built in 2011 for the Solidays festival in Paris to house 500 people. Developed by gridshell researcher Olivier Bavarel and his six student collaborators, it consists of two humps, one larger than the other. The structure measured 7m high, 26 m long with a width of 15m and covers an area of approximately 280 m2. The structure is made of a composite glass fibre reinforced polymer plastic (GFRP). The circular tubes were of two diameters, measuring 13.4mm and 41.7mm in girth respectively. The gridmat was first constructed flat on the ground first. Special swivel scaffolding elements were used for constructing the gridmat. To deform and erect the gridshell, two cranes were used.

It took about 10 people to work on the erection. Further GFRP bracing elements triangulate, brace and rigidify the grid units to induce in-plane stiffness. When the bracing process was complete, the gridshell became form-active. For this project, the protective cladding was supplied by tightly stretching a polypropylene welded PVC canvas over the gridshell until there were no wrinkles (Baverel, O., Caron, J. F., Tayeb, F., & Peloux, L. D., 2012).

5.5 Evaluation of Technology:

Through seminal examples of both deployable and actively bent gridshells, advantages and disadvantages of the system are observed to form an assessment of this technology.

5.5.1 Advantages of Deployable Actively-Bent Gridshells:

- Because deployable gridshells are collapsible / they could be space-saving. The ability to collapse and close up and be stored away is a valuable quality. This also suggests that the gridmat may be passed through very small openings. These can prove useful in terms of portability and transportability as pointed out by Hernández, and Gengnagel, 2014.

- Reusability : the Montreal 1967 National Pavilion designed for the World Expo was an exercise in portability having been first built in Germany, then closed up and re-erected in Germany.
- Re-configurability. Depending on how the smaller sections are made up, the deployable gridshell can be joined together to form larger or smaller sections (Chapter 6.2.4)
- Deployable gridhells are force-responsive. Changes to shape can be introduced by applying forces to make use of the gridmat's ability to self-adjust to forces. As such, the deployable nature of gridshell at smaller scales could make them useful as physical models. This helps the creative designer understand forces intuitively and non-mathematically.
- Gridshells can be strong structures. However, their ability to respond in form depends on their material choice and grid density. Deployable gridshells in timber and GFRP require different forces to effect shape changes.
- Deployable gridshells can be beautiful structures.
- They span large distances and can cover large areas.
- The construction of gridshells by pushing the shell upwards may reduce and/or eradicate the use of costly and cumbersome scaffolding or other falsework that supports the structure. Compared to the drop-down method employed by The Weald and Downland and Savill gridshell, the possibility to push the structure upwards is useful.
- As gridshells derive strength from their shape and not mass, being able to span large distances and shelter large areas; using little material, their thinness implies an efficient economy of material use. This makes gridshells appropriate and attractive as an architectural option in our resource-conscious environment.

5.5.2 Disadvantages of Deployable Actively-Bent Gridshells:

- Construction of gridshells is time-consuming and labour-intensive. It was pointed out that although it took only hours for 10 people to construct the GFRP Solidays gridshell, it can take several weeks to prepare materials and components (Tayeb, F., Baverel, O., Caron, J. F., & Du Peloux, 2013). Depending on the forming method, the construction period may be long as well. For example, it took six months for the gridmat to relax into its final shape at the Weald and Downland Gridshell (2003).
- Despite digital advances, gridshells remain complex structures to understand, even for the engineer. It can be difficult to form-find and understand the effects of forces on geometry and vice-versa. A physical sketch model of a deployable gridshell may become helpful and intuitive in facilitating a preliminary understanding of gridshell behaviour.
- Gridshells can be expensive not in terms of materials in design costs requiring specialist labour - in design and in actual construction.
- With so many joints in the gridshell, the use of repeated and identical elements such as pre-drilled laths and rotating fastenings can work out costly in small numbers. However, when mass- produced, the unit cost of components may become cheaper. To reduce cost, digital fabrication technology may be employed. Although materials are not expensive, specialist skills, such as form-finding specialists could add cost to a project involving gridshells.
- As deployable gridshells use long laths, they can become fragile to handle and be susceptible to breakages. Also, due to long continuous lengths of flexible material involved, deployable gridshells require large working spaces for materials to be manoeuvred. As a result, many deployed gridshells are constructed on greenfield sites e.g. open woodland and park landscapes offering space. At the Savill gridshell construction, to prevent breakages, long laths of timber were passed through long lengths of PVC piping to be transported from one level to another.
- When long laths break, they may be difficult to be repaired/ replaced as they are physically connected to the structure of the deployed gridmat.

"...during the assembly of project Essen: due to inherent stresses, several grid rods directly next to joints were broken" (Otto, Burkhart and Hennicke 1974, p. 219).

At Mannheim "... quite a number of finger joints broke on site during handling and erection" (Happold and Liddell 1976, p. 126).

Fractured hemlock pine sections at Mannheim Multihalle were repaired by screwing additional timber sections on either sides. In the Downland gridshell, "of the 10 000 joints in the structure, there were approximately 145 breakages during forming. Almost all were failures of the finger joints" (Harris, Haskins and Roynon, p 437). Finally, in the Savill Garden grid shell, there were only two fractures during the construction process possibly due to their low curvatures and also perhaps the design team has used an effective way to transport long timber laths with pvc drain pipes as discussed earlier (Chilton and Tang, 2017).

- The process of lifting and forming requires specialist scaffolding and cranes with cost implications. The Solidays project required cranes whilst the extensive use of PERI props were used at the Japan pavilion (2000), the Downland and Saville (2002) and Savill gridshell (2005) (Chilton and Tang, 2017).
- Depending on gridshell material, forming process can be time-consuming. The gridshell at Weald and Downland took over six months to deform. However, the Solidays pavilion crafted from GFRP was very quickly erected in 10 hours (Tayeb, F., Baverel, O., Caron, J. F., & Du Peloux, 2013). As such, construction time is highly variable, often interpreted as a risk in the risk-averse construction industry.
- To brace and connect points on the gridshell through triangulation bracing to induce in-plane stability could also be labour intensive (Hernandez and Gangnagel, 2014), thus adding time and labour cost to the project.
- Openings at high level may require bespoke detailing seen in the two polycarbonate side clerestory strips at the Weald and Downland gridshell.
- Over time, depending on their material, actively bent gridshells may suffer from deflection and creep: leading to irreversible deformation. The permanent deformation of Mannheim Multihalle Gridshell, currently supported by timber props bears witness to this difficulty.
- The issue of the outer covering is a problem frequently encountered by the deployable gridshell. Traditionally, this is achieved by pre-stressed membrane/ skin to enclose the gridshell. Material choice and mechanism for fixing membrane material onto a double curving surface are also complex design exercises. The problem of forming a continuous surface is different from concrete shells as in the latter, the structure and skin works in unity. Therefore, the type of covering impacts on the accuracy required of the structure.

5.5.3 Active Bending: Suitable Materials

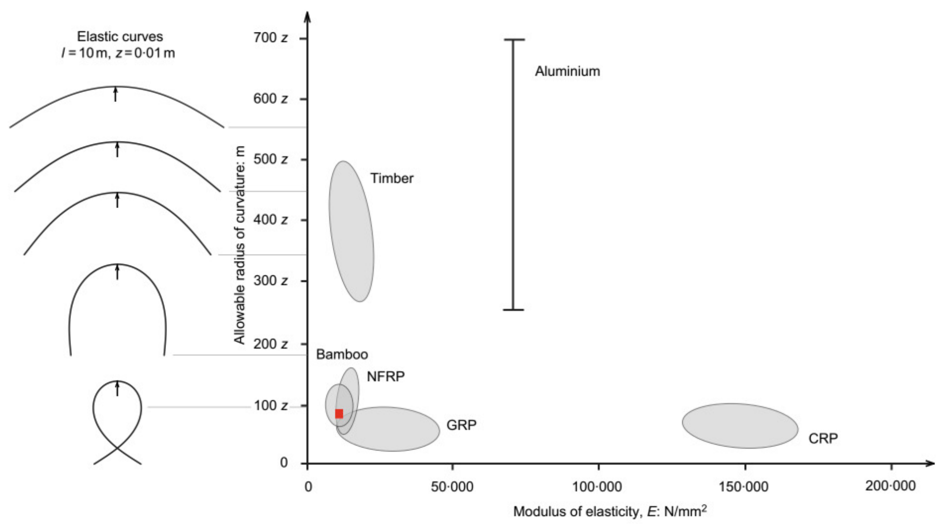


Fig 5.15 Material properties with respect to bending (Genangnal, 2013)

Traditionally, gridshells are constructed in timber. However, being a natural material with inconsistencies in structural properties, alternative materials must also be considered to be used as primary shell structure.

The above graph (Gengnagel et al, 2010, 2013) describes a comparison between suitable materials used in active bending structures specifically in consideration for deployable gridshells construction use. It shows that although timber is effective in the past, glass reinforced plastics (GRP) are much more flexible and elastic than timber. The study also explored the suitability of natural fibres reinforced plastics (NFRP) as a viable material for constructing gridshells.

5.5.4 Conclusion:

Constructing deployable and actively bent gridshells is time-consuming (both design and construction times). This often involved extensive on-site fixings to stabilize and brace the structure. Apart from construction times, component preparation may be long too. Traditionally, deployable and actively-bent gridshells are constructed in timber. However, recent interests in the use of other synthetic materials such as GFRP with more structural consistency are considered. GFRP have a constant Young's Modulus and a high yield stress for the material to return to their original state. The choice of suitable material for deployable gridshells is of paramount importance to the success to a formwork system that employs them.

5.6 Gridshell student workshops and the birth of the Hypothesis:

> *"The only way you can build, the only way you can get the building into being, is through the measurable. You must follow the laws of nature and use quantities of brick, methods of construction, and engineering. But in the end, when the building becomes part of living, it evokes the unmeasurable qualities and the spirit of existence takes over."*
>
> *Louis I Kahn, (taken from Carpenter, 1997)*

Designer as Constructor: Construction Workshops – A Hands-On Material Pedagogy

Building is an essential part of learning about design and materials by constructing and through creative play advocated by the prolific concrete shell designer Heinz Isler (Chilton, 2000 p28). Isler believed creative play is the mother of creative invention and effective innovation. The proposal of using deployable gridshells as formwork was born through a series of construction workshops carried out in the spirit of flash research (Benjamin, 2012) with past students working with the author in his work as an educator. The following workshops aimed to develop an intuitive understanding of deployable gridshells, resulting in a catalogue of student workshop, through the path of success and failure, which led to the genesis of the hypothesis and subsequent line of inquiry. Through these workshops, the potential of deployability became clear.

Fig 5.16 A series of construction student workshops were organised to explore the idea of deployability in actively bent gridshells.

Fig 5.16 describe a series of student construction workshops liken to *Flash* research in Chapter 2.6 (Benjamin, 2012) involving model-making, rapid-prototyping, a limited budget within a restricted time-frame (a week) was organised to explore the behaviour and the construction of deployable gridshell. 2008 saw the first workshop conducted at Sheffield Hallam University, followed by a next one at The Royal Academy of Fine Arts Copenhagen in 2010. In 2011, a large scale gridshell workshop involved the participation of the entire school. This was significant as it was at this 2011 student workshop that the hypothesis of this research enquiry came into being. Following that, a last workshop entitled *Material Connections* was organised in 2013 to expand the potential of using deployable gridshells as formwork to construct concrete shells. This last workshop is discussed in Chapter 6.6.2 (The Hypothesis).

5.6.1 Workshop 1: Gridshell Structures Workshop with Studio Cullinan, 2008

Aim: To explore and learn about the basic principle of deployable gridshells, their construction and their behaviour.

Process:

Together with architects Emily (Jack) Henningsen and John Romer (architect in the team at Edward Cullinan's Architects who worked on the 2002 Weald and Downland gridshell) a student workshop was organised to understand construction of deployable gridshells through the process of construction.

Materials:

1.5m long bamboo canes and plastic cable ties were used. Avoiding the need to drill to anchor into the timber floor, four raised elliptical platforms 1.2m x 1.8m 18mm mdf boards were pre-drilled with 5mm diameter holes spaced out 100mm around the edges. These 18mm mdf boards were raised above with 2 x 2 softwood planks were heavy to serve as anchor plates to support the bamboo gridshell.

Fig. 5.17 The first composite arches defined the shape of the students' first design solution. Although structurally sound, the students' first design solution was unevenly spaced and asymmetrical.

Two gridshells in bamboo were built during this one day workshop: the first one in an instinctive manner, and secondly in a method inspired by the actual construction of the Downland gridshell.

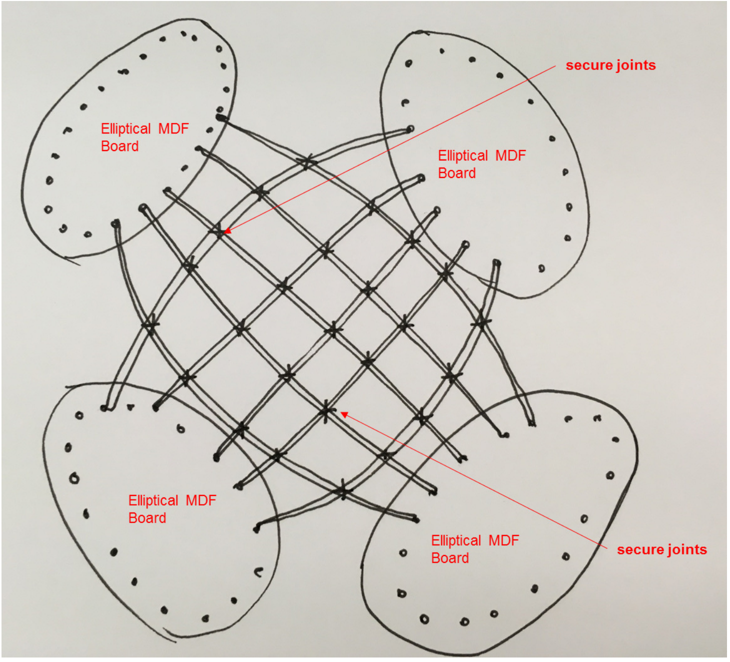


Fig. 5.18 Plan of the first activity involved 4 mdf boards drilled with holes at the periphery where bamboo laths were inserted between them.

For the first gridshell, having no given instructions, students took oval base-boards and arranged them as shown in fig. 5.18. Bamboo canes were then inserted into the pre-drilled holes. After that, they extended the bamboo canes by using 2 cable ties until the cane arched downwards to be inserted into a hole located in the base-plate diagonally opposite the base plate. With one student supporting an arch made earlier, another group repeated the process to form another arch. These 2 arches were tied together at their intersections at the apex to create a self-supporting structure. The students then proceeded to repeat this process crossing arches, weaving the material into a basket-like bee-hive shape structure. Although this was an interesting sequence which achieved a gridshell, the spacing between the bamboo cane arches was irregular and asymmetrical (fig. 5.17).

For the second shell, all bamboo materials were removed. Following that, John Romer explained the principles of a gridshell. A circle three meter diameter was marked out on the floor using chalk and measuring tape. Two pieces of extended bamboo poles (primary canes) 3 meters long were first laid out on the floor. The canes were extended by securing each overlap of the two pieces of 1.5m long bamboo cane together by fastening 2 cable ties spaced 30cm apart.

Fig. 5.19 The gridshell started to take shape, rising from the ground, as each student walked towards the centre of the circle. To support the gridshell, chairs were used to "prop" each constituent bamboo cane. The ring of chairs served the equivalent of a ring beam that supported the grid members. (left) A bamboo lattice to a circle of diameter 3m was formed. The canes were laid out on 0.5m spacing.

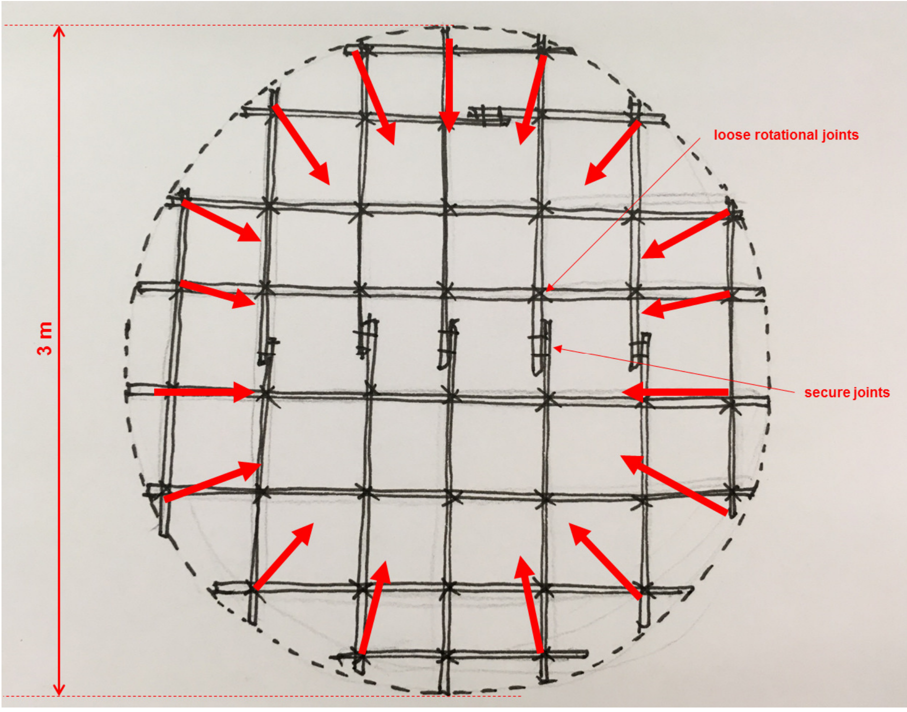


Fig 5. 20 (bottom) plan of the construction showing connections to extend each member as well as locations of rotational cross joints. When students held each point and walked towards the middle, a three dimensional shell was formed.

A lattice of 0.5m spacing was made by laying bamboo poles. Cable-ties loosely held the 2 intersecting canes in position. It was important for this fixing to be loose to allow intersecting bamboo canes to rotate freely when gridmat was raised. Students were each assigned to one of the bamboo cane around the perimeter of the lattice. With each student holding the cane at each end, the gridmat was carefully raised from the ground. With this gridshell raised above ground and kept slightly bent, the students held the ends of the canes and walked towards the centre of the circle. With each step, every extended bamboo lath became actively-bent.

Results:
The lattice grid mat rose from the flat ground to become a grid-shell. This time, the grid appeared more evenly spaced out. In contrast with the first attempt, the construction illustrated the importance of construction techniques in actively-bent gridshells. The construction of deployable gridshell experienced and learnt as seen from the transformation of the gridshell from a flat gridmat to a three dimensional form. Bamboo and plastic cable ties were cheap and easily available material for demonstrating the principles of deployable gridshells. The workshop took a day to run and the materials 1 full day took 2 workshop technicians to fabricate in one full day.

5.6.2 Workshop 2: 2010 Royal Academy of Fine Arts, Copenhagen 8th – 13th March 2010, Royal Academy of Fine Arts, Copenhagen, Denmark

Aim: To further develop design possibilities of gridshells constructed of bamboo.

Process: Developing from the initial 2008 workshop in Sheffield, bamboo gridshells were explored further. A physical investigation of gridshells in bamboo was made using thin balsa wood bent into different curvatures. The design was inspired by one of Leonardo da Vinci's flying machines and resembled two intersecting wings.

In this example, the grids in the gridshell were not evenly spaced as was seen in the example before. A grassed area in the academy courtyard was used for the gridshell to be constructed. The bamboo struts were spliced together using cable ties to form longer lath elements and then tied together at the intersections with cable ties. The structure was simply inserted into the soft ground by pushing the ends of the bamboo into the earth. As the structure was lightweight, it was not braced or triangulated.

Material: Each bamboo pole measured two metres long. With a circular diameter of 10mm, these 2 m long bamboo poles appeared stiff. When they were spliced and joined up to form longer laths, they became very flexible. Spliced together tightly using plastic cable ties to prevent slipping, the construction process used a straightforward and low-tech method that required unskilled labour. The result was a bamboo gridshell that measured 5.6m x 3m.

Fig 5.21a physical model made from stiff pine sections measuring 5mmx 5mm in profile.(Gabriel Tang)

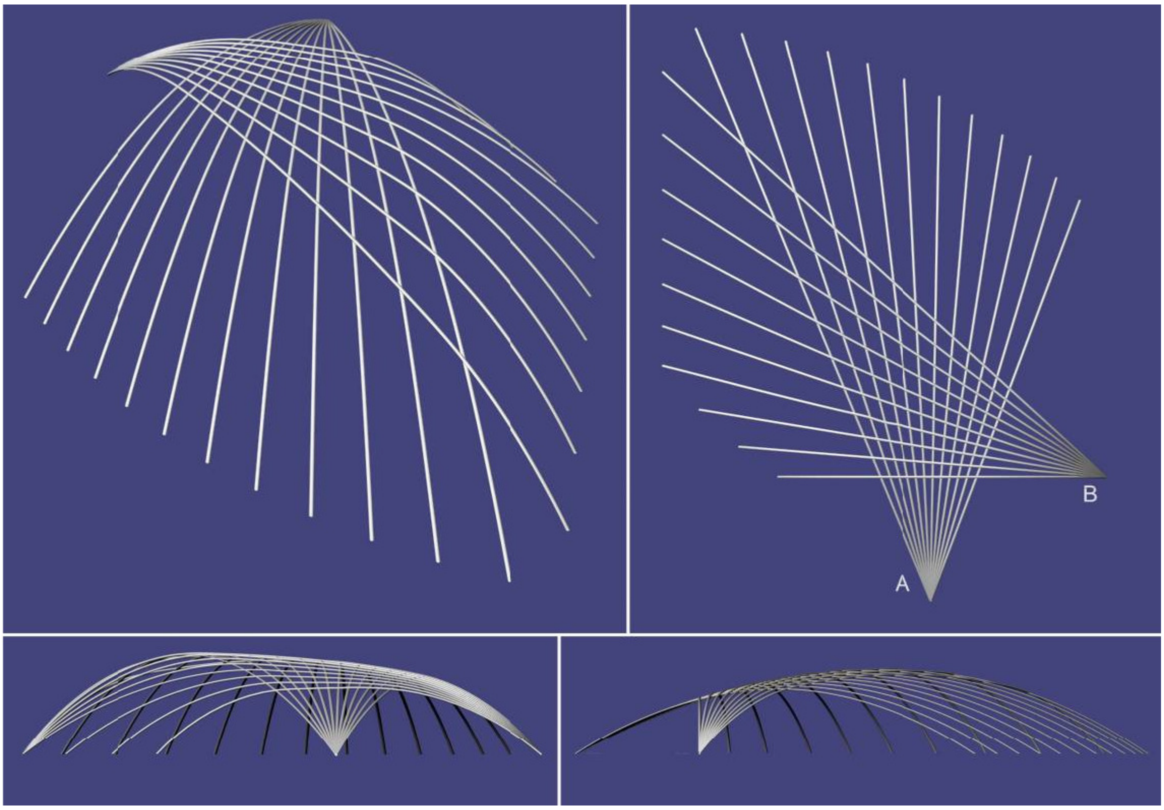


Fig. 5.22: (right) digital model of the bamboo gridshell (drawn by Dr D. Lee).

Fig 5.23 The final structure on the grassed area at Royal Academy of Fine Arts Copenhagen (Gabriel Tang)

Fig 5.24 The final structure on the grassed area at Royal Academy of Fine Arts Copenhagen (Gabriel Tang).

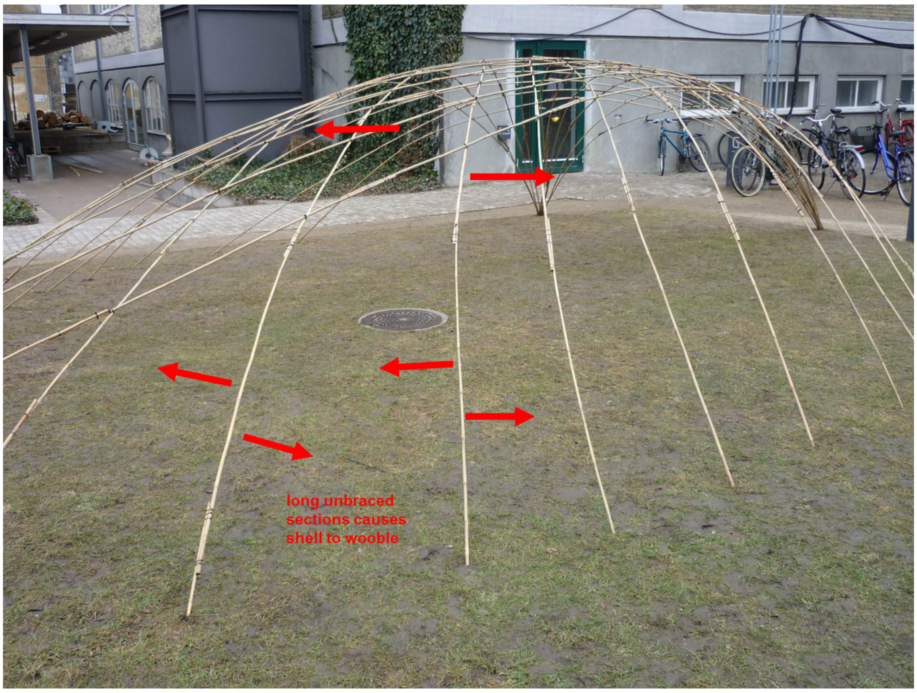


Fig 5.25 Simple plastic cable tie joining details shows the emphasis of the irregularity of bamboo (Gabriel Tang).

The resulting gridshell was flexible and light (both materially and visually). The structure was unstable and experienced deflection due to the long unbraced ends that touched the ground. More bracing could induce additional in-plane stiffness for rigidity. The gridshell was not braced but depended on tight cable tie joints to provide rigid joints. This unevenness of the structure was noticeable when viewed at close proximity. The black-coloured plastic cable ties also highlighted inconsistencies of grid spacing and methods of connecting bamboo canes together.

Results:

This construction workshop reaffirmed the possibility of using bamboo as a material for actively bent gridshells. The unstable behaviour of the gridshell highlighted the importance of sufficient bracing to induce effective lateral stability. The bamboo laths were gathered together and bundled into a hollow rectangular steel section in the ground. Rounded profiles of bamboo canes were difficult to splice together with cable ties. It was also difficult to form intersection joints which led to an “untidy” appearance and inaccuracy of construction.

The use of scaled models as design tool was useful as a instrument of communication but the timber section did not best represent the flexible nature of bamboo poles at long lengths. The model displayed stiff behaviour of the timber members which was not the flexible behaviour of the actual bamboo gridshell.

The results raised questions about bamboo’s suitability as gridshell construction material at this scale to exploit its flexible nature. Although bamboo (1-5 years old phyllostachys pubescens) was found to be a suitable material for active-bending (Gengnagel, Hernández and Bäumer, 2013), as having good bending radius and high modulus of elasticity (value of 8.680-13.410), its irregularity and tectonic quality may require further consideration before its eventual selection.

5.6.3 Workshop 3: Timber Gridshell Workshop, Sheffield Hallam University, 2011

The workshop at Sheffield Hallam University in 2011 was a culmination of lessons learnt from workshops organised and carried out in the past.

Chosen for their aesthetic value, this design exercise made use of pine timber laths with a rectangular profile dimensioning 35 mm x 12 mm. Compared to bamboo canes used in Denmark in 2010, the timber laths were more conspicuous and much more sharply defined to give a precise finish. The flat surfaces also provided more surface area for better rotation motion. In this test, instead of cable ties, M5 metal nuts and bolts were used to create swivel joints, resulting in an engineered appearance when compared to cable ties used previously. The flat surfaces also made drilling easier with their flat surfaces.

Fig 5.26 The two gridshells sat at the grassed area in Sheffield City Centre.

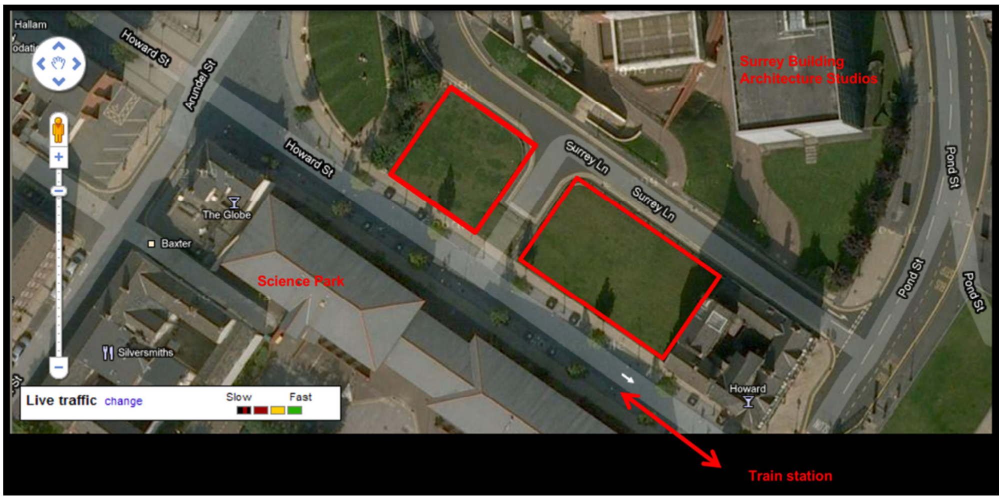


Fig 5.27 The sites were at the grounds of University City Campus along the way to Sheffield train station.

Designing the shell

Instead of digital form-finding, the design was developed by the use of a gridmat model constructed from 5mm wide, 0.5 mm thick paste cards cut into long strips and cross laid and pinned together to emulate the deformation of the actual gridmat. The gridmat was constructed at a scale of 1:50. The loose scissor joints were pin-jointed together by 20mm model pins. Mats with square grids were made and arranged at a diagonal to the edges as shown in figures below.

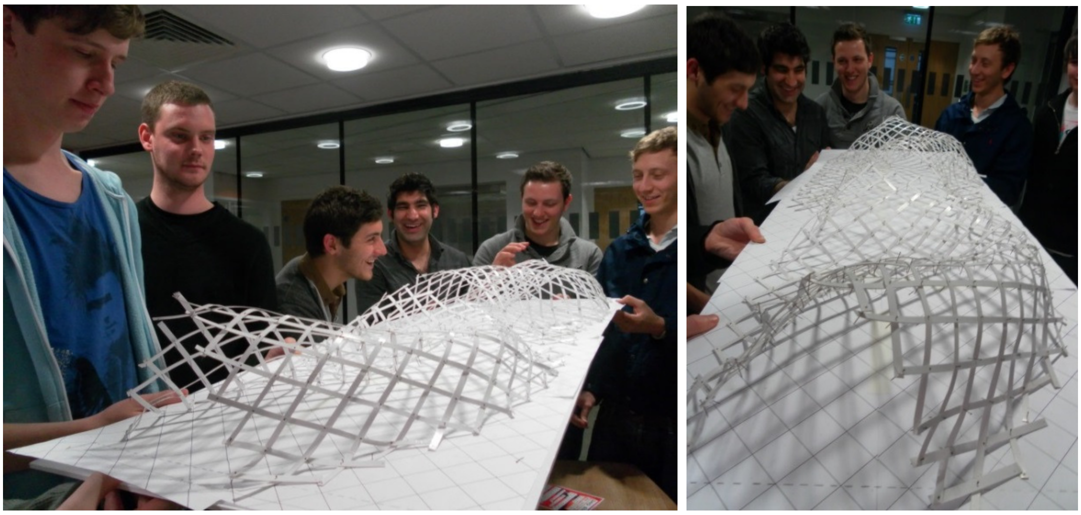


Fig 5.28 Actively bent gridshells were constructed at 1:50 using paper cards. (credit Gabriel Tang)

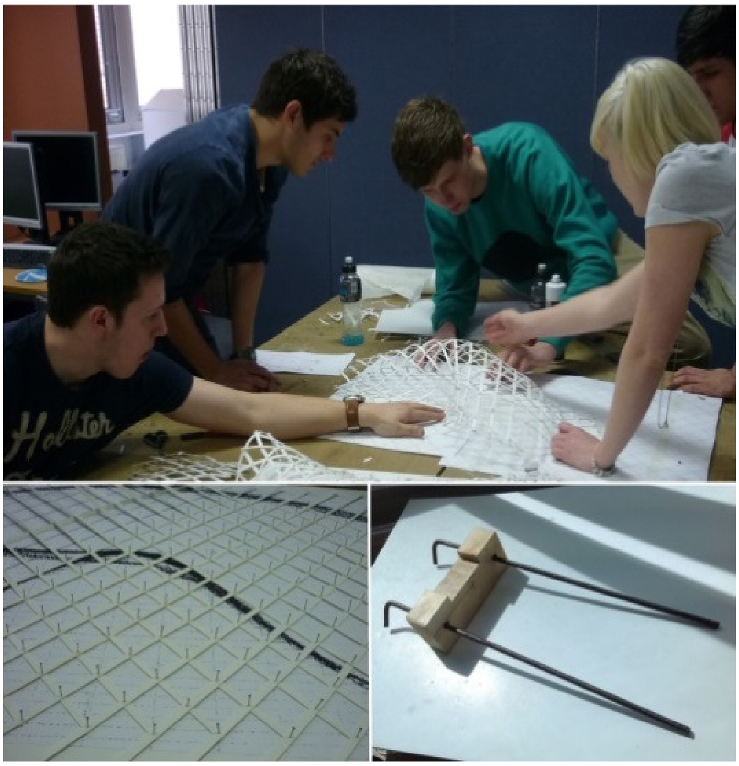


Fig 5.29 (top) students in the process of designing actively-bent gridshell.
(bottom left): flat gridmat was built by cross laying paper card strips and pinning them down to create free rotation joints.
(bottom right): wooden blocks and re-bar chairs for anchoring sections of the gridshell into the ground (credit Gabriel Tang)

These mats deformed by pushing them from away from the edges. Twisting and manipulating these gridmats, the mat rose, contracted, expanded and three-dimensionalised, resulting in doubly-curved structures. When bending forces were applied, and with particular points restrained, the deformation could be controlled. The timber gridshell was also constructed in a single layer, as opposed to a double layer.

Timber Testing

Fig 5.30 Left: timber failure tests. Right: Flat gridmat assembled on ground.

Pine timbers were failure tested to a circular curve of 2.25 m radius which was the radius worked out by Gordon Cowley as a workable radius of bending for a timber of this dimension. This was done by holding down the lath over a timber block of a radius 2.25m (fig 5.30 left). By doing this, only suitable timbers were used to avoid replacing and repairing the timbers should any members were to break- a problem as experienced in Mannheim Multihalle (1976) gridshell.

Fig 5.31 top left: Wooden blocks and re-bar chairs were hammered into the ground to secure the gridshell.
top right: timber sections were extended by double bolting an overlap lath.
bottom : gridshell that was in a bee-hive shape

Initial construction took place in the rain. Excitedly, the pre-drilled timber laths were laid out on the ground on a single layer with a grid 900 x 900mm to form a mat measuring 10m by 10m. The scissor joints were encouraged to rotate by the placement of double washers through m5 mild steel bolts. A single bulging synclastic shell was created. The structure was positioned along the incline of the grassed bank which sloped away towards Sheffield train station. In the frenzy and in the rain, communication was difficult with all participants trying deciding on a final shape resulting in the shell constructed organically without an actual plan.

To secure the gridshell, pre-made steel chairs and timber anchors were hammered into the soft earth. To brace the structure, each quadrilateral diagrids was triangulated by adding bracing. Without a co-ordinated method to build, given the weather conditions, it was difficult to co-ordinate the erection process. This resulted in a gridshell insufficiently braced without the complete triangulation of all grids. With the weather deteriorating, the gridshell was left overnight on the grass exposed to heavy rain that ensued.

Fig 5.32; The first gridshell, although arching confidently did not withstand the attack of weather.

As the gridshell was built on a slope falling towards the train station, the gridshell collapsed completely. It had snapped and failed on the lower side. Positioned prominently, it was imperative this was rectified. The broken gridmat was set aside whilst a new shell at the lower lawns was designed, addressing lessons learnt forensically outlined below.

Unfortunately, after a continuous night of rainfall, the gridshell collapsed at 1am on 17th March 2011. Images received from the university central security systems revealed how the structure failed and collapsed. This is attributed to the orientation of the structure (fig. 5.34).

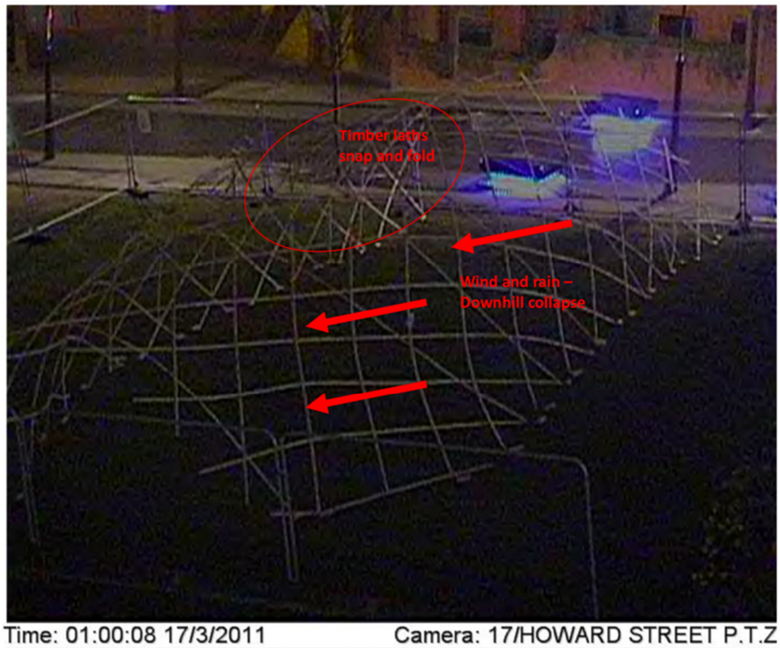


Fig 5.33 Initial collapse

Fig 5.34 Eventual collapse

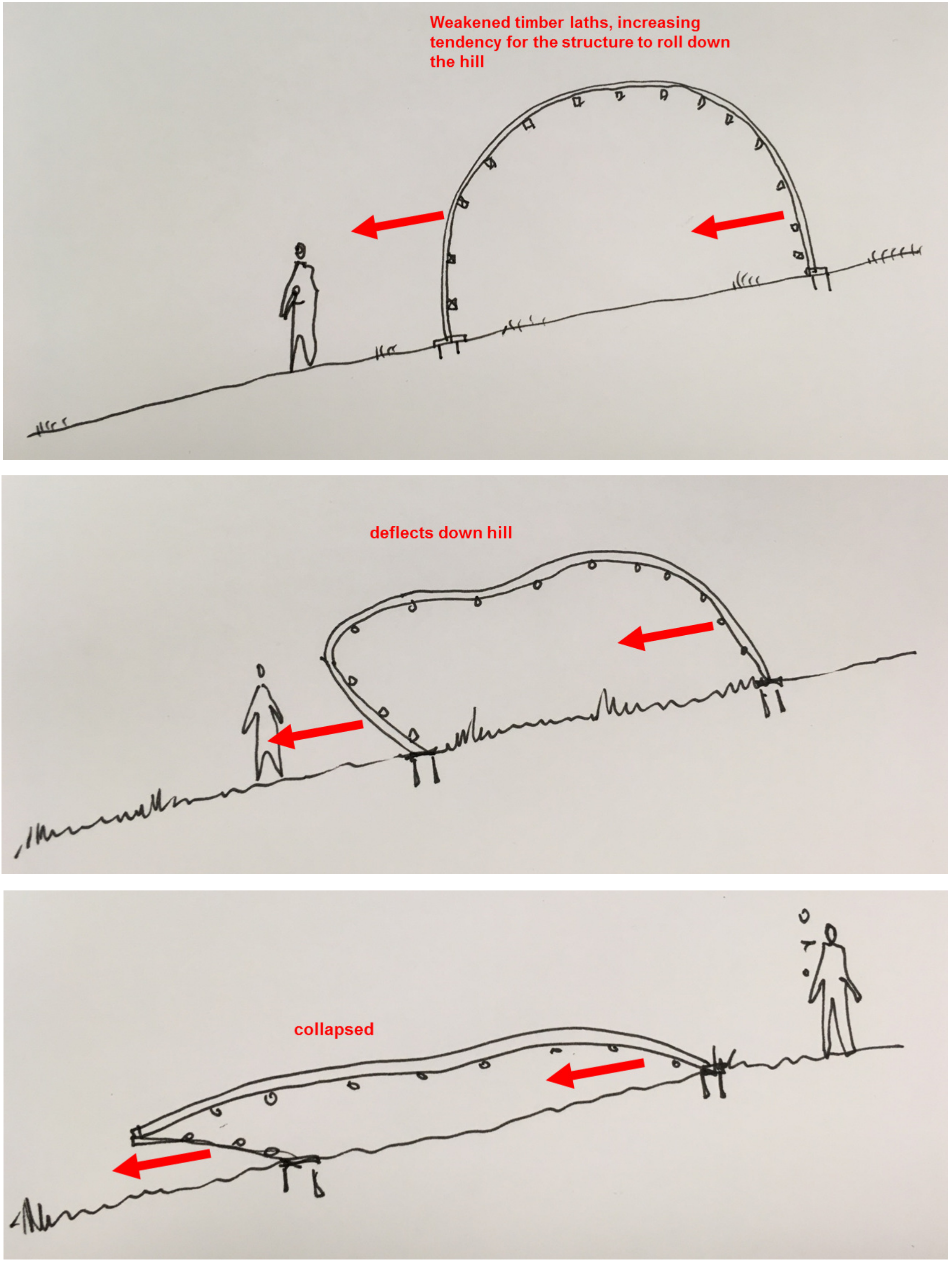


Fig 5.35 Stages of Collapse: top: Shell has a tendency to "roll" downhill.
middle: wind loading causes the shell to deflect downwards on the hill.
bottom: with rain attacking the structural integrity of indoor grade, timbers failed at the weakest points and fractured.

Re-Design

The security images fig 5.33 and 5.34 revealed how the design could be improved:

- Bracing: The gridshell must be braced completely to provide sufficient stiffness and stability. However, this may increase time and material use.
- Communication of erection stages: gridshell was erected without careful choreography where everyone carrying a part of the gridshell knew where they were heading – i.e. towards or away from each other. The confusion in the rain caused workshop participants to become

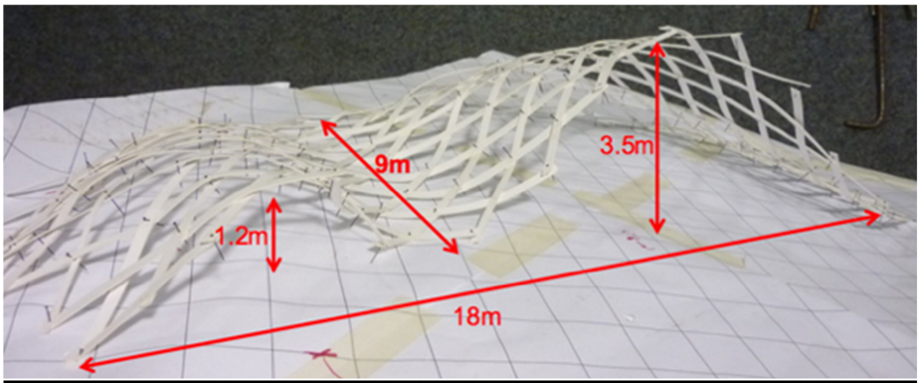
disorganised. Communication and stages of construction must be fully understood by all constructors involved.

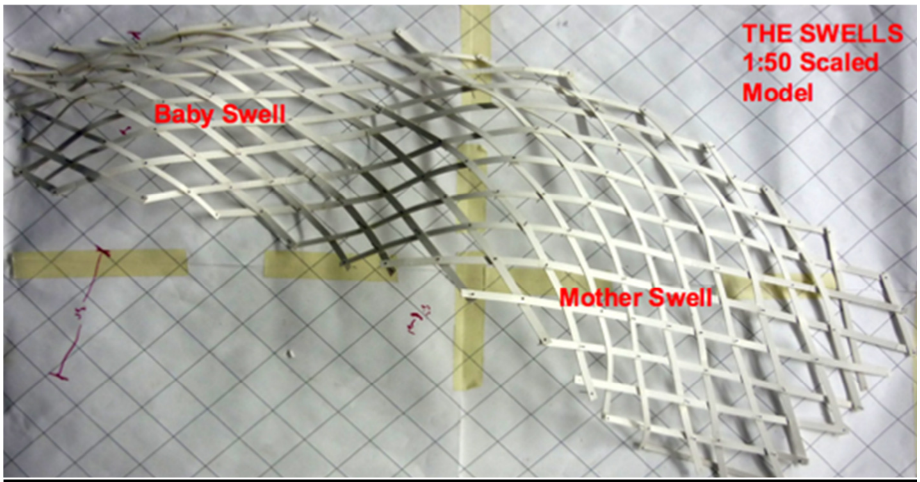
- Additional anchoring may be required to anchor the structure down better: especially in areas prone to high winds, the gridshell was not tethered into the ground properly to prevent it from lifted by the wind.
- Attention to the free-edge, the edge conditions around the gridshell must be reinforced by doubling up for the elements to act as an edge stabiliser.

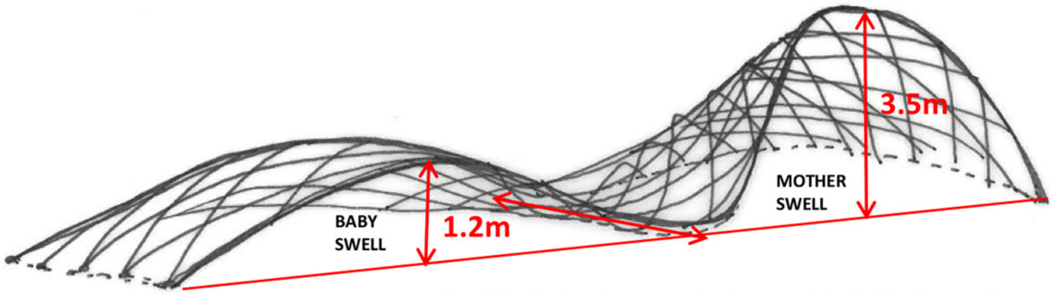
<u>The Swells</u>

The new structure that resulted was entitled The Swells and was made from new timber laths. As the name suggests, the gridshell consisted of 2 swells – firstly, the larger one rising to a height of 3.5 m whilst a smaller swell rising to a height of 1.2 metres. The undulations were created by the same gridmat that measured approximately 9m x 18m. The front edges were free and rose out of the ground whereas the back was completely anchored using the same system of anchor blocks and steel chairs hammered into the ground. The entire section is anchored to the ground completely. The grids worked well with the pre-drilled timber laths and the grids measuring 900 x 900mm.

Fig 5.36 The Swells being constructed with grids measuring 900mm by 900mm.







the gridshell is directly connected to the ground attached to the ground.
However, this will not allow the gridshell to be removed.

Fig 5.37. The timber gridshell was composed of two free-edges one 3.5m and another 1.2m..

Fig 5.38 The Swells being constructed. In the far distance, the fallen first shell was visible on the upper lawn.

Fig 5.39. The timber gridshell composed of two free-edges being constructed in 2011.

Learning from past experience, the stages of erection was now thoroughly rehearsed with all constructors knowing the exact direction in which direction to move. It was also learnt that the gridmat deformed more easily after being extended to loosen the tight mechanical joints. Learning from collapse failure, the gridshell was extensively braced this time with long laths to triangulate the structure. The sequence of construction was much more systematic and organised compared to before. This time, the construction processes was also clearly communicated with the team. The gridshell was extensively anchored and well-tethered to the ground with ropes.

Fig 5.40 The Leaf

The Leaf

The fallen grid mat was reinstated and the unbroken section salvaged to create a new gridshell addressing many of the lessons learnt. What remained was a gridmat deformed previously and re-used to create a sharp and pointed form. It was re-shaped into a partial structure resembling a leaf resting on the grassed earth. The endings of the gridmat tapered to a point and were lifted 1.5 metres away from the ground being tied back to the main gridshell with ropes. The free edges of the gridshell were reinforced by timber laths to produce a shell with double curvature. Again, this structure was securely braced and anchored onto the ground.

5.6.4 Deployable gridmat as Structurally Intuitive design tool.

Evidently, the same system of gridmat was reconfigured from a single bulbous hive-shaped gridshell into a leaf shaped doubly-curving gridshell. This was facilitated by the simulation of a scaled paper model where all constructors could see and understand the erection stages. This is an intuitive and interesting way of creating temporary structures.

5.6.5 Important Observation: Reshaping and re-using the same grid mat

After outdoor installation, the two structures were taken down. Firstly, tethering ropes were taken down. The bracing laths were then disconnected. At this point, the actively bent timber gridshell reverted to its original flat state, returning to becoming the original grid-mat. The gridmat is a material that could be re-deployed and be stored away in sections. They were labelled accordingly with the view to re-use as a re-configured assembly of a gridshell, with a new geometry in the future.

Fig 5.41 The gridshell was taken apart in sections and stored away for future use.

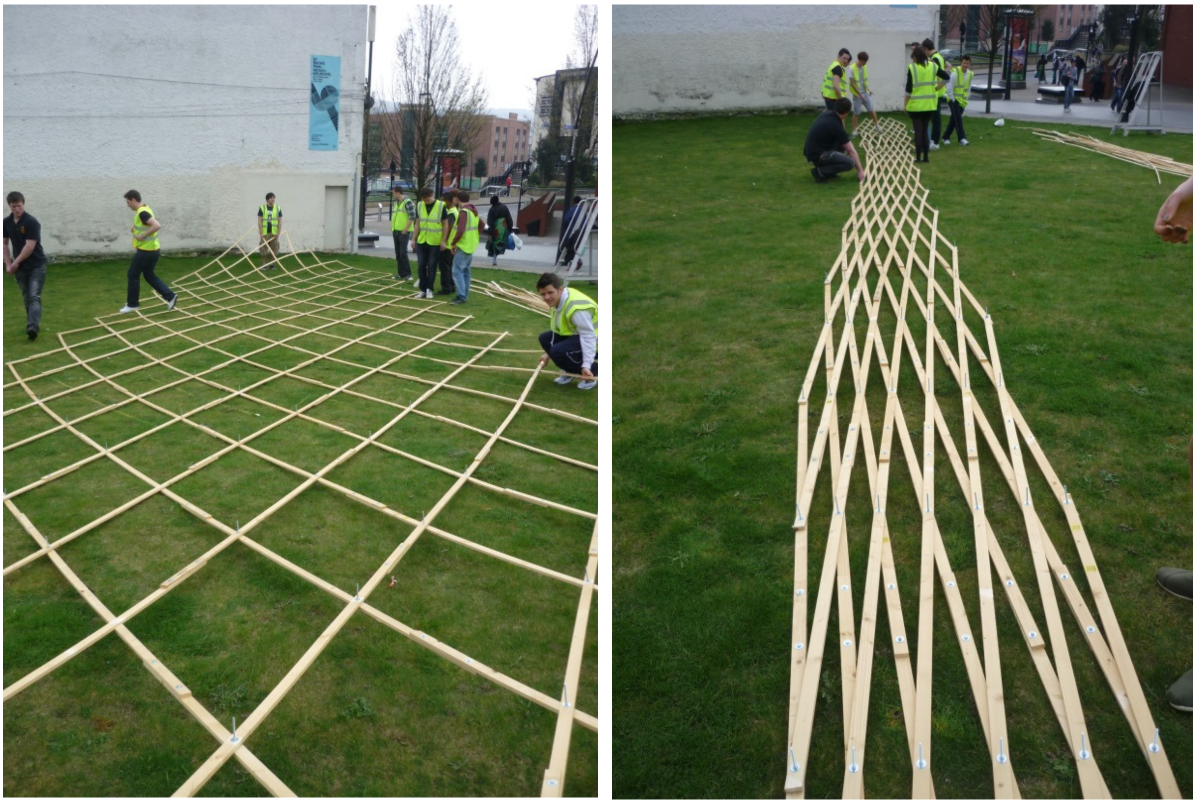


Fig 5.42 The gridshell flattened out and was collapsed away.

5.7 Discussion

Construction workshops like these are practical ways of learning about constructing gridshells. Through this form of *Flash* research, new ideas are trialled which developed an empirical understanding of the construction process and the relationship with various elements of gridshell design in two principal ways:

5.7.1 Relationship between Shape and Design

Although pure compression shells are not always possible with shell shapes produced by bending gridshell members, the gridmat and its ability to change shape to enclose a space is very useful for the designer who has many strict planning parameters to fulfil (e.g. heights and floor areas). When dealing with shells, designers need an understanding of space requirements to enclose a large space or provide shelter. The gridmat is helpful for the designer to work out the deformation stages systematically.

5.7.2 Relationship between forces and construction

The 2011 workshop proved the use of the deployable gridmat as a way of understanding the design scenario through physical modelling, similar to how Mannheim Multihalle was form-found. The model was useful in demonstrating the process of deforming dynamically which communicates with constructors. In the design of the Weald and Downland gridshell, the model also helped the design team understand and fine-tune dynamic relaxation of the shell where deformation stages were carefully considered to determine the sequence of deformation (Harris, 2003). The responsive nature of the gridmat to deform and become three-dimensional is a behaviour that deserves further investigation. The ways by which anticlastic, synclastic and monoclastic geometries (Chapter 3.2.3) of shells can be achieved from a single deployable lattice is interesting.

5.7.3 Relationship between Shape and Construction

Double curvatures create stiffer shapes. The failure to provide double curvatures is attributed to the collapse of the first bee-hive shape shell. With the Swells, an interesting observation was made about the structural behaviour. The area where the geometry changes, i.e. where it was flat, were found to be highly deflective whilst areas with defined and strong double curvatures were much stiffer and did not yield to the same imposed force (i.e. by simply pushing the hand against the shell).

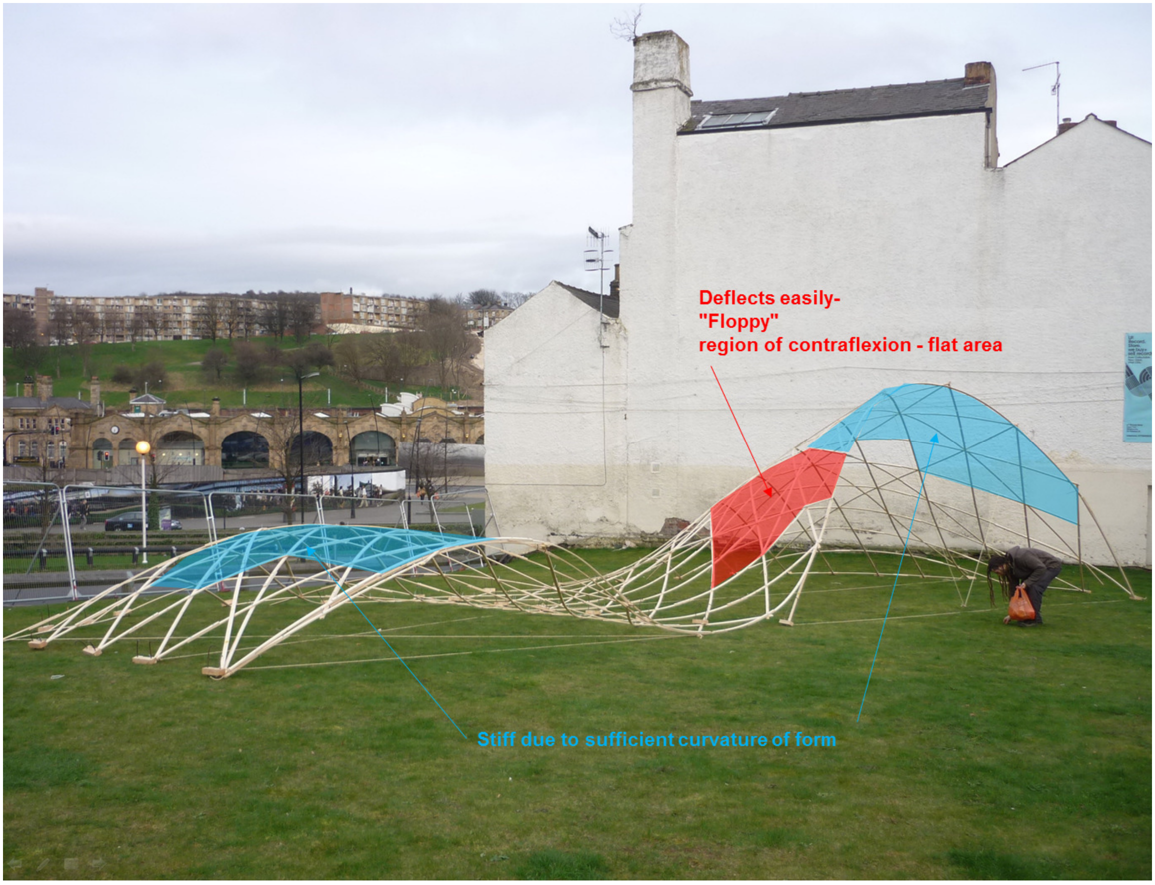


Fig 5.43 The gridshell was taken apart in sections and stored away for future use.

Challenges were noticed in this construction exercise:

- The lack of consistency in structural/ mechanical property of timber led to the initial collapse in wet weather. Timber, being a natural material, has knots and imperfections. 40% of the timbers tested did not satisfy structural requirements. As such, a great amount of material was wasted during the process. This suggests the consideration of another material for use as an alternative gridshell material more weather stable than timber such as fibre glass reinforced plastics, glass reinforced plastics or carbon fibres which need to be considered as alternatives.

- Timber was easy to cut, drill and bend. Timber, compared to steel or concrete, is a forgiving material and was easy to work with. Timber is suitable as a material for extending laths or use as bracing laths.

- The construction exercise was labour-intensive and time-consuming. The workshop in 2011 required approximately 25 students to construct during the week. However, the preparation of steel chairs and pre-drilling of timber laths was long too. This experience is similar with the observations at the Solidays gridshell which attributed much time and labour in preparation phase.

- The exercise importantly revealed the re-use and reconfigurability of gridshells.

5.8 Conclusion: Key Finding and Research Idea

The key finding from this exercise saw formwork reconfigure and be reused, something that other systems of concrete shell formwork (discussed in Chapter 3.7) could not perform and/ or offer. This adaptability of the mat in terms of size also meant that grid mat could be enlarged or reduced according to use or application (to be discussed in Chapter 6.2.4). The ability to extend, contract and collapse before and after erection is a major advantage with benefits of storage ease and transportability.

The workshop therefore uncovered characteristics of deployable gridshell, namely reusability and reconfigurability addressing key internal issues about shortcoming of present formwork systems critically outlined in Chapter 3.9. Specifically, they relate to present shortcomings of concrete shell formwork discussed in Chapter 3.4.

The main reason why concrete shells lost their popularity is partly due to the limitations of formwork methods in that present concrete shell formwork are:

- not usually designed for reuse (and if they are, produces a monotony in forms)
- not usually designed to be re-configurable (and if they are, do not relate to structural principles - making structures often arbitrary and problematic, both structurally and in construction terms)
- not intuitive for the designer (architect and/or engineer) to understand how forces affect shell shaping and vice-versa. A gap is identified between the process of form-making and shell construction.

The use of deployable gridshells as formwork for concrete shell construction is an intriguing concept with enormous potential to address issues concrete shell formwork systems could not. As such, the 2011 construction workshop marks the beginning of an idea that combines three related structural systems - concrete shells, fabric formwork and deployable gridshell as re-configurable, temporary re-usable, deployable and actively-bent formwork to construct concrete shells.

The research question and hypothesis which unifies the above technologies will be elaborated in the following chapter.

Mixing Concrete, Nanjing Southeast University, 2016 (Gabriel Tang)

PART 3 CONSTRUCTION AND TESTING

Chapter 6 HYPOTHESIS

Chapter 6: The Hypothesis

6.1 Introduction

The aim of this chapter is three-fold:

- to synthesize the ideas from concrete shells, fabric formworks and deployable gridshells
- to interrogate and elaborate the hypothesis
- to devise construction tests with a focus on specific aims for empirical results to support the hypothesis.

6.2 Key Aspects and Further Questions of the Hypothesis

6.2.1. Fabric as formwork

The 2011 Sheffield student construction workshop (chapter 5.6) raised specific questions about this idea answerable through a series of focussed construction tests. A fundamental question relates to how concrete is actually supported between the 900mm x 900mm grids to support the wet concrete. One method is to use fabric stretched over the entire gridshell structure as surface formwork. This idea is akin to Lilienthal's 1899 patent for a suspended concrete floor discussed in chapter 4.7.

Possibilities of working with fabric are outlined:

Referring to fig 6.1 below, we see gridshells used as a framework where fabric is stretched over to create a surface onto which concrete is applied. Wire mesh is laid within the concrete depth and embedded within the concrete shell itself.

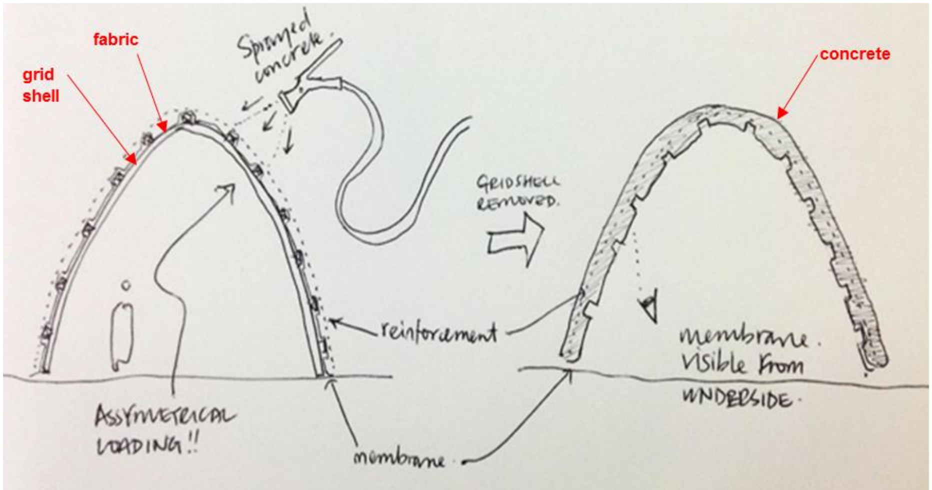


Fig 6.1 left: concrete is sprayed onto fabric stretched over a rigidized deployable gridshell. right: the complete shell

Other options of insulating concrete are possible and rigid insulation can be embedded and cast into the concrete:

a) Referring to fig 6.2: rigid insulation is inserted in between grids spaces in the gridshell to provide shear plates to rigidify the structure. This will need to be a very tight fit. Fabric is then placed above and a thin layer of concrete is sprayed on top. When the concrete hardens, the gridshell is decentred with insulation intact on the resultant concrete shell. There are two key disadvantages with this method. Firstly, for them to stay in place on the gridshell the tight fit of the rigid insulation is difficult to control. Secondly, this changes the aesthetic and removes benefits of thermal mass of the shell with insulation covering the internal surfaces of the shell.

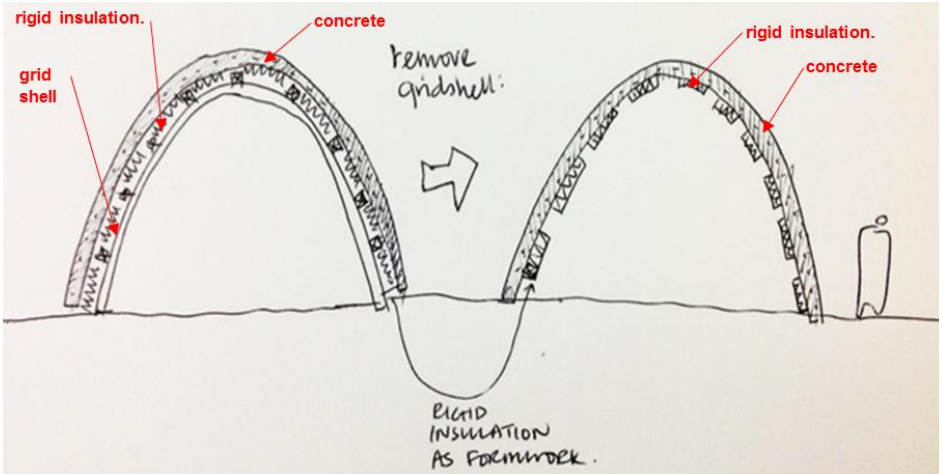


Fig 6.2 Rigid insulation between gridmats stiffens the gridshell and then concrete applied over the surface.

6.2.2. Form Richness of concrete shell

Deployable gridshell construction leads to a variation of form expression not restricted to geometric monotony of technologies of pneumatic formworks such as Bini shells. This hypothesis is attractive through its portability, reusability and be re-configurability.

The flexibility of form change and re-configurability by joining sections to enlarge or reduce grid size can lead to infinite possibilities of morphologies. Gridshells, with strong double curvatures induced by temporary stiffness while braced, can be reversibly flattened, then re-shaped to support a concrete cast. This idea is attractive, with an impact to the environment in sustainability terms.

6.2.3. Re-usability

Depending on the gridshell material, it may be used repeatedly to create shells of the same geometry. Depending on the design, it may not be necessary to completely take the gridshell apart into individual laths. Formwork may be removed and used completely as a single element, as illustrated in fig 6.3, envisaged most efficiently to produce repeated shell series. The cost of concrete formwork drops from 60% of total cost of construction to 40% after five re-uses (Lee and McAdam, 2010).

6.2.4. Re-configurability

Re-configurability on this system can be interpreted in two ways:

- The first assumes that the flat mat is of the same size and reconfigured into different shapes/ forms with double curvatures.

- The second assumes the flat mat as extended or contracted to create shells of different sizes, and of different geometries.

This flexibility is an attractive aspect not offered by the pneumatic formwork.

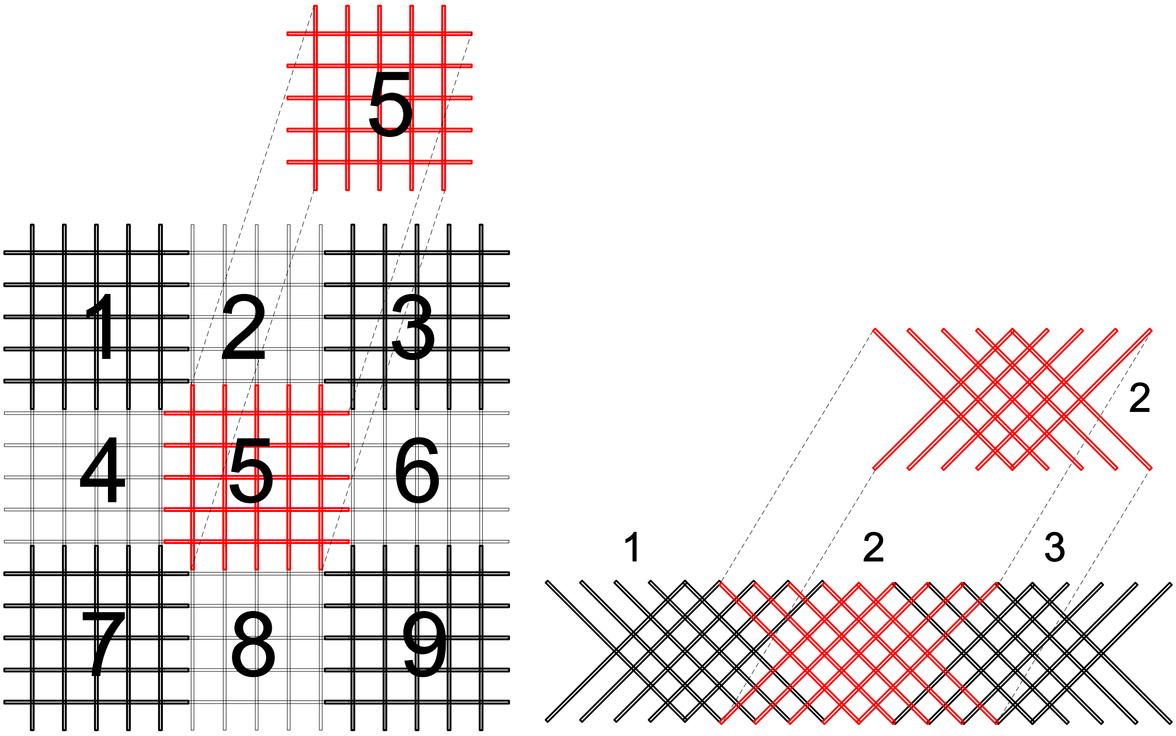


Fig 6.3 The variation of piecing sections of pre-made gridmat modules together to form larger gridmats of different orientations in relation to the edges.

6.2.5. Cost

With formwork materials and equipment constituting up to 60% of builder's on-site investment (Lyngcoln in Lee and McAdam, 1997), a formwork system that adds value would be crucial to see its commercial acceptance. The proposed system is argued to allay cost concerns faced by bespoke profile timber formwork of specific curvatures made for creating one-off shells as conducted by Isler. Only with strong working relationship with the contractor to re-use these forms to repeatedly create multiple shells for the same project, could Isler keep the cost low. Ideally, if the re-configurability of the deployable gridshell into infinite structurally efficient forms is possible, it will offer something that all other systems were not able to offer, with positive impact on cost, efficiency and material economy.

6.2.6. Minimising **scaffolding and supports (falsework)**

The proposal may minimise internal scaffolding as gridshells could bear concrete dead-load at the first place. Upon curing, this first thin layer of concrete could support subsequent concrete layers. This benefit may have an impact on cost. Without a forest of scaffolding to carry the fibre-glass tube gridshell, internal walls or floors in less obstructed spaces could be built. The eradication of scaffolding implies time-saving benefits. Instead of using scaffolding to support the gridshell, alternatives to temporary shuttering supports could be explored. Pneumatic formwork (the use of an inflated balloon to raise and support a deployable gridshell for example) has been proposed by Quinn and Gengnagel (2014).

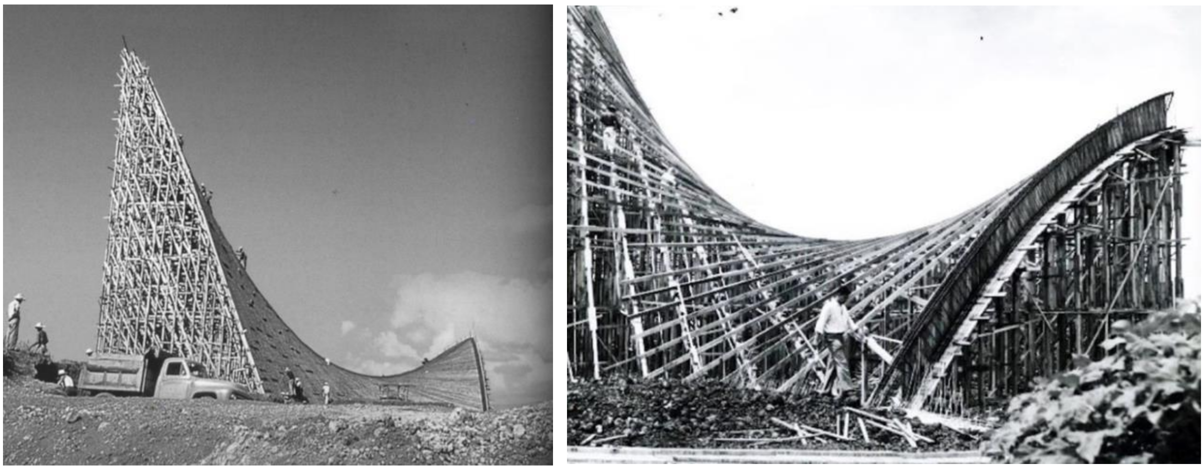
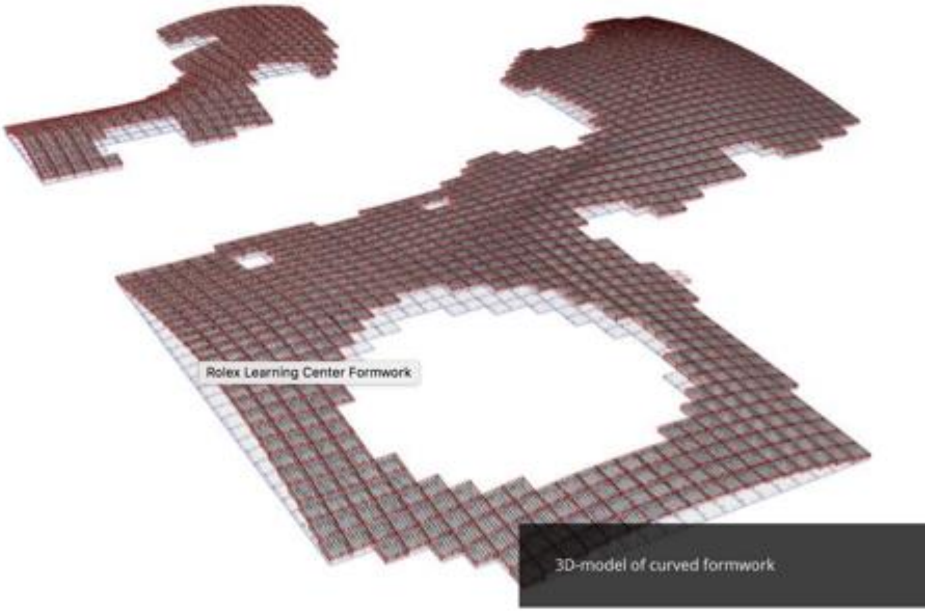


Fig. 6.4 The concrete shells of Felix Candela required intensive use of temporary support to form doubly-curved surface upon which concrete was applied.

Minimising shell supports is a running challenge for shell designers. Presented by Krosomer and Kolleger, their 2014 proposal to raise a segmented fresh concrete supported by a pneumatic formwork from the ground, aimed to remove the need for scaffolding (as discussed in Chapter 3.6.4.1). The crane was used on numerous occasions. Baveral et al (2012) used cranes to lift the GFRP gridshell from the ground in the Cretail and Solidays GFRP gridshells (Chapter 5.4.2.2). The crane was also used for the Essen gridshell project (discussed in Chapter 5.4.1) by Frei Otto. Gridshells can also be pushed up from the ground after gridmat assembly as seen in Mannheim Multihalle (Chapter 5.4.1.1).

In the Rolex Centre by SANAA (Chapter 3.2.1.5) and the Kikimigahara concrete shell (Chapter 3.6.1.6) by Toyo Ito, the design and cutting of OSB to fabricate scaffolding tables can be labour intensive and wastes offcut material. Technology e.g. computer modelling and sophisticated CAD/CAM fabrication method has allowed these to be fabricated easily.



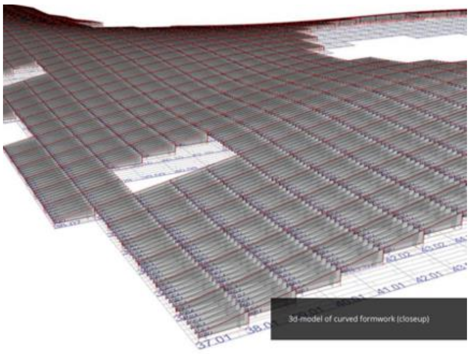


Fig. 6.5 ROLEX CENTRE EPFL, Lausanne SANAA
illustrates the extensive discretization of OSB (oriented strand boards) supporting “tables” to create a continuous surface upon which concrete is poured to form the undulating surface of the Rolex Centre at EPFL, Switzerland, in a structure not strictly in pure compression.

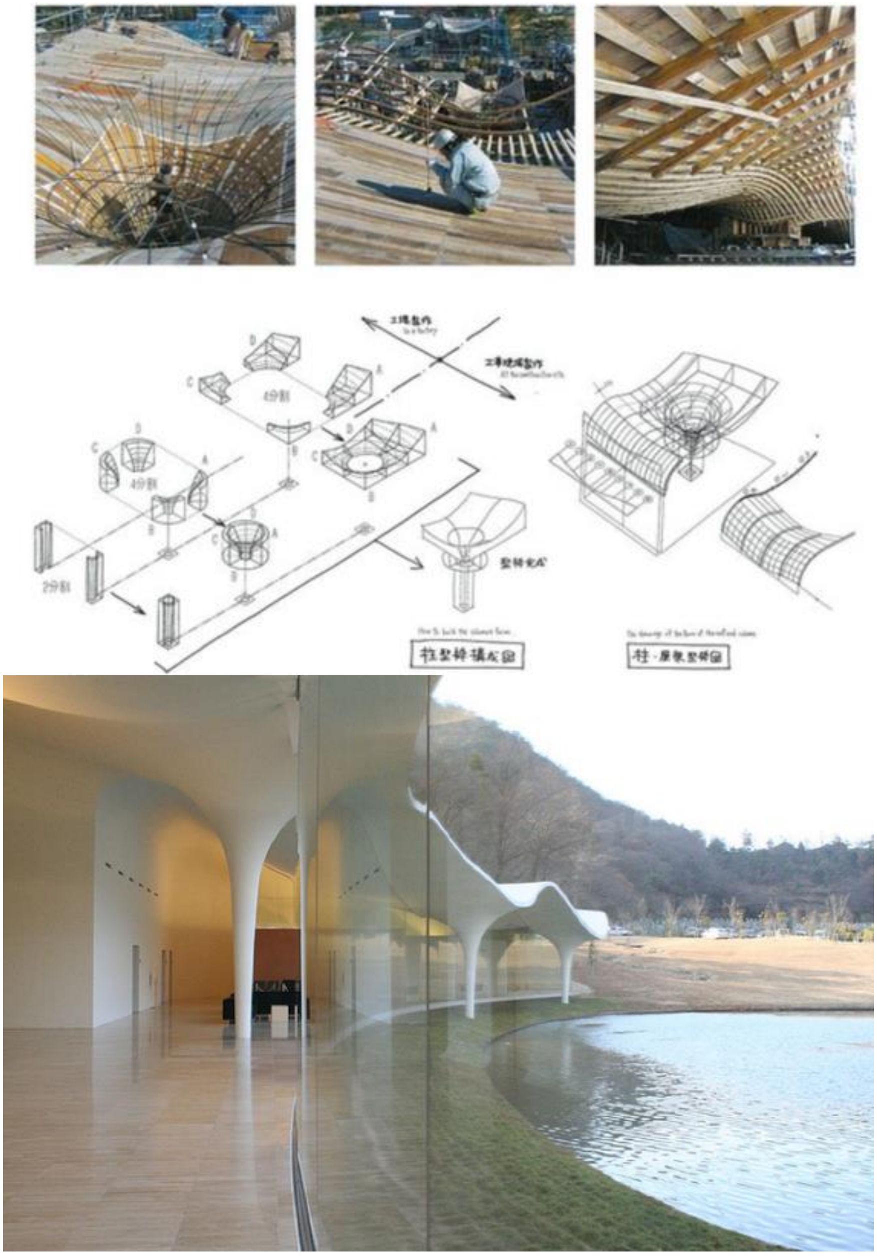


Fig. 6.6 Kikimigahara Crematorium shell:
The cloud-like billowing roof form was the result of concrete poured onto a continuous surface created with timber by skilful craftspeople. A combination of special plywood moulds were constructed as well as the use of more traditional timber supports.

6.2.7. Sustainability

The hypothesis is sustainable in the following ways:

6.2.7.1 System Reuse

In environmentally responsible construction practices, construction technologies and methods must be taken into account through constructing sustainability guidelines. (McDonough, 1992 and Naik, 2008). Formwork use is found to reduce material involved in the construction process. Additionally, this reduces the use of formwork such as plywood commonly discarded after casting. Hence, the proposal eliminates the manufacture of bespoke one-use formwork.

6.2.7.2 Recycling Of System

Due to their re-configurability, gridshells as formwork could be recycled and reused in repeated castings (same shape) or reconfigured for multiple castings (different shapes). Depending on conditions, fabric material may also be reused. In this sense, cost saving can be achieved by repeated gridshell formwork reuse.

6.2.7.3 Material frugality: optimising structural strength from form, not mass.

The method of form-finding encourages an informed structural solution conforming to statics and structural logic. Proper concrete shells (i.e. of pure compression) and improper gridshells (with bending moments) allow designs to exploit efficient shell forms with minimal bending. This, in turn allows them to be thin and hence be materially-efficient. Thinness results in concrete minimisation as shells span larger distances. This results in structures which are efficient in material use and increased sustainability.

6.2.7.4 Adaptability and Re-use.

Resultant concrete shells enclose wide-spanning spaces and have long life-spans. These wide-spanning structures are adaptable as they roof large spaces that allow structures under these shells to be adapted in response to changes in building functions/ requirements. The CNIT shell clearly illustrated this when it underwent refurbishments in 1988 and subsequently 2009 to incorporate new hotels, shops and offices as discussed in Chapter 3.6.1.4.

6.2.7.5 Thermal mass benefits of concrete shells.

Exposed concrete on internal surfaces of shells provide thermal mass. Exposed concrete absorbs heat from internal spaces and release heat back into the space when internal atmosphere is cool. The ability for concrete to regulate internal environments is an attractive property. This relies on concrete surfaces being exposed to the internal environment for this advantage to be enjoyed.

6.3 Deployable Gridshell as Form-finding and Form-making Tool

Chapter 3.3.12 discussed the discrepancy between form-finding and construction. This resulted in formwork becoming bespoke (i.e. not re-configurable) and expensive which has partly led to the demise of concrete shells. Gridshells as formwork can close this gap directly to address this observation.

In Chapter 3.2.2.1, the perfect compression shell was defined by the catenary form of the hanging chain (Hooke's Law). Designers in the past have used this fact to design and form-find efficient funicular masonry structures. In the same way that masonry vaults were form-found through hanging chains, the perfect shape for concrete shells acting in complete compression can be derived from inverting pure compression hanging chain or membranes exemplified by Heinz Isler's hanging membrane method of form-finding (Chilton, 2000).

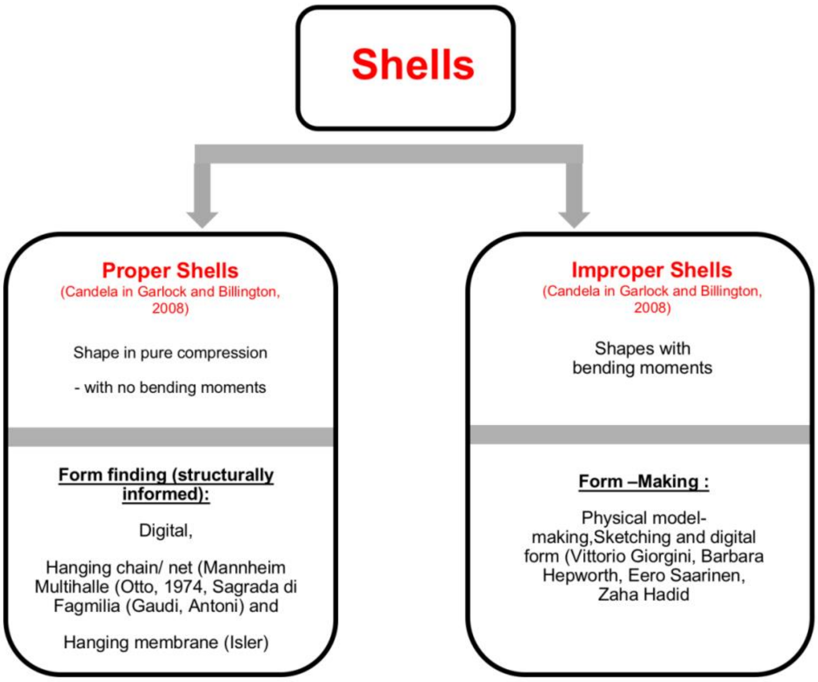
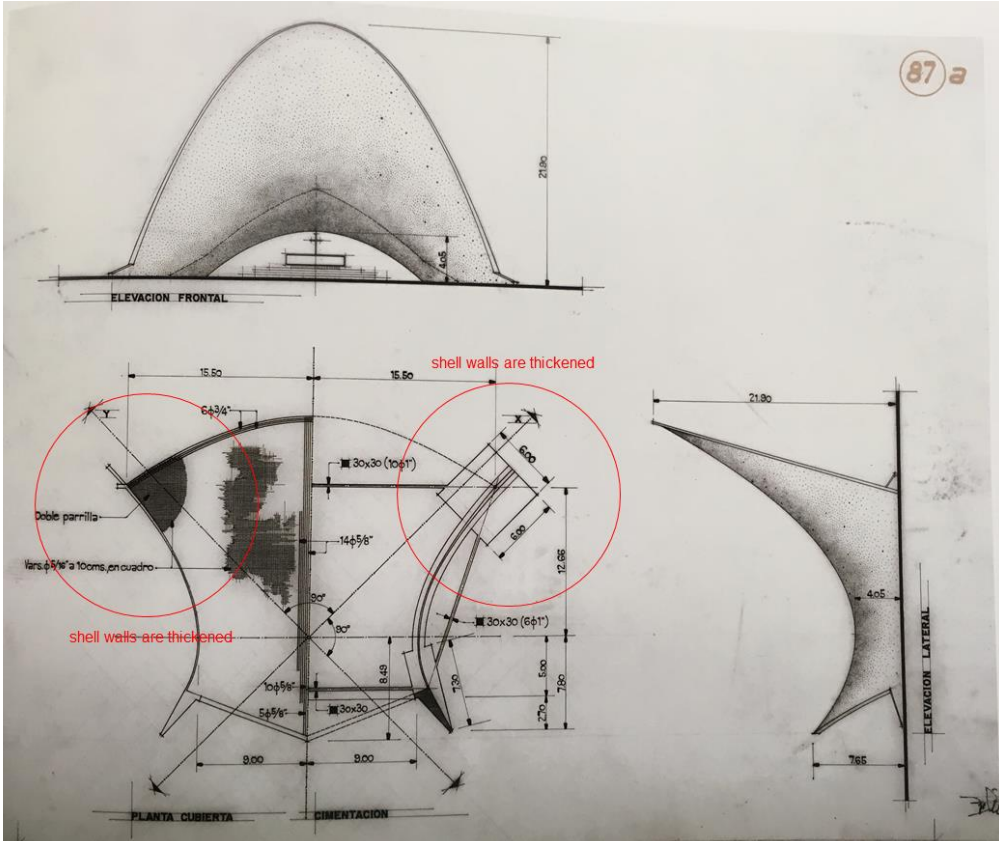


Fig. 6.7 The classification of Shells and their relationship to form-finding/ form-making methods.

Upon close examination, concrete shells can be classified as either *"proper"* or *"improper"* (Candela in Garlock and Billington, 2008). *Proper shells* act in pure compression and conform to catenary lines defined by hanging nets. These were used by Antoni Gaudi and Frei Otto in form-finding purely compressive shapes which defined forms in pure tension. This theory pertains to Hooke's Law that recognises that when inverted, pure tension hanging chain nets will act in pure compression.

To counteract imperfect force conditions, reinforcements and/ or thickening of shell walls helps address undesirable bending stresses. To counteract high compressive stresses found in the shell, Candela thickened the walls near the abutments at the Chapel de Lomas concrete shell in Cuernavaca, 1958. This is illustrated in figure below:



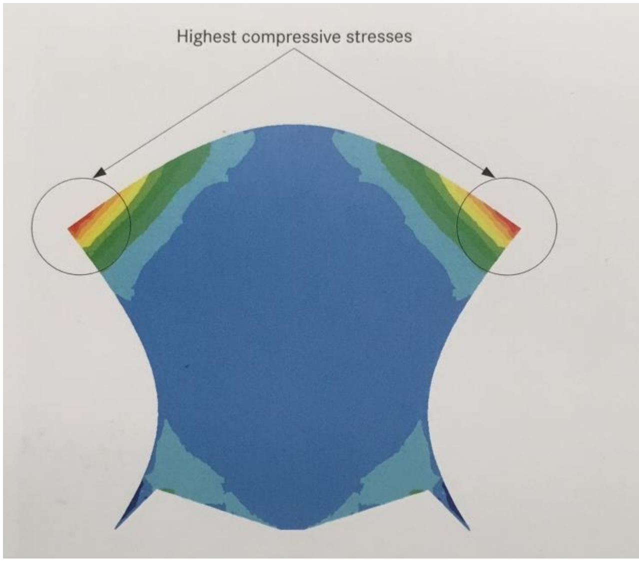


Figure 6.8 walls at shell anchors of shells are thickened to counteract high compressive forces. (taken from Garlock and Billington, 2008)

On the other hand, improper shells are subject to bending stresses and could be form found digitally or through model making. Improper shells are subject to bending stresses.

The PhD hypothesis is not about form-finding per se i.e. optimisation of pure compression shell shapes as precisely defined by Hennicke and Shaur in IL 10 (1974). Rather, the hypothesis suggests a method of creating shell structures that considers structure, architecture, craft, economics, aesthetics and construction methods. This method could contribute as one way of understanding how form, material, forces and architectural space interact and address constructional difficulties.

6.3.1 Gridshells as Form Finding Tool (Proper Shells)

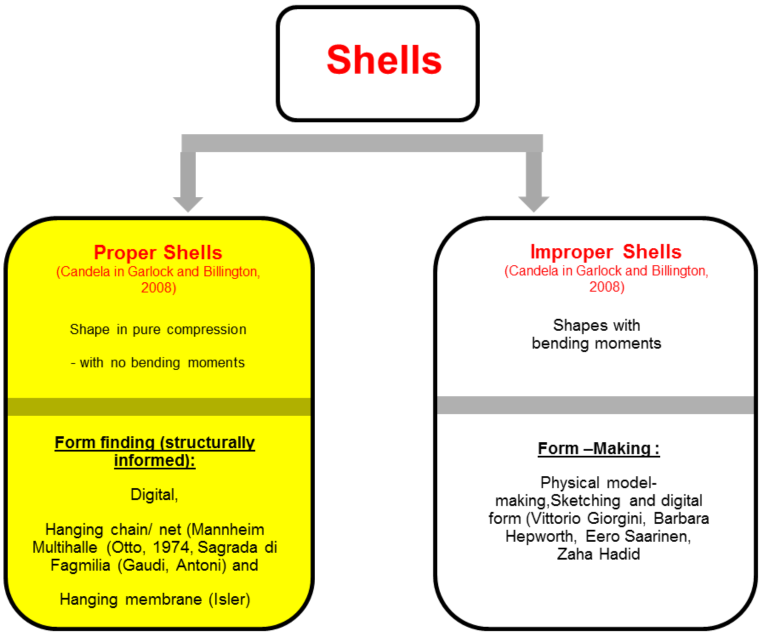


Fig 6.9 From the same gridmat, proper shells are easily designed to respect the elastic ratio of the materials in question.

Deployable gridshells as formwork for *proper shells*.

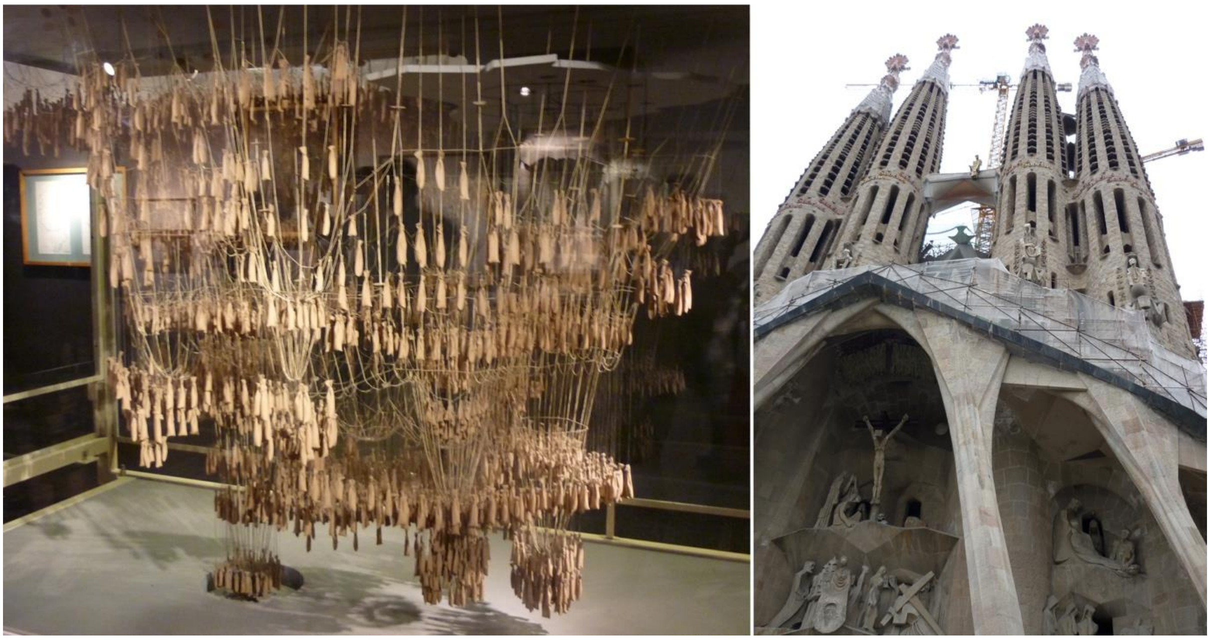


Fig 6.10 From the same gridmat, proper shells are designed to respect the elastic ratio of the materials in question.

Variation 1

The principle of the use by hanging chain model is created with a specified grid size. This is then suspended on a frame to create a form in pure tension shown in fig. 6.11.

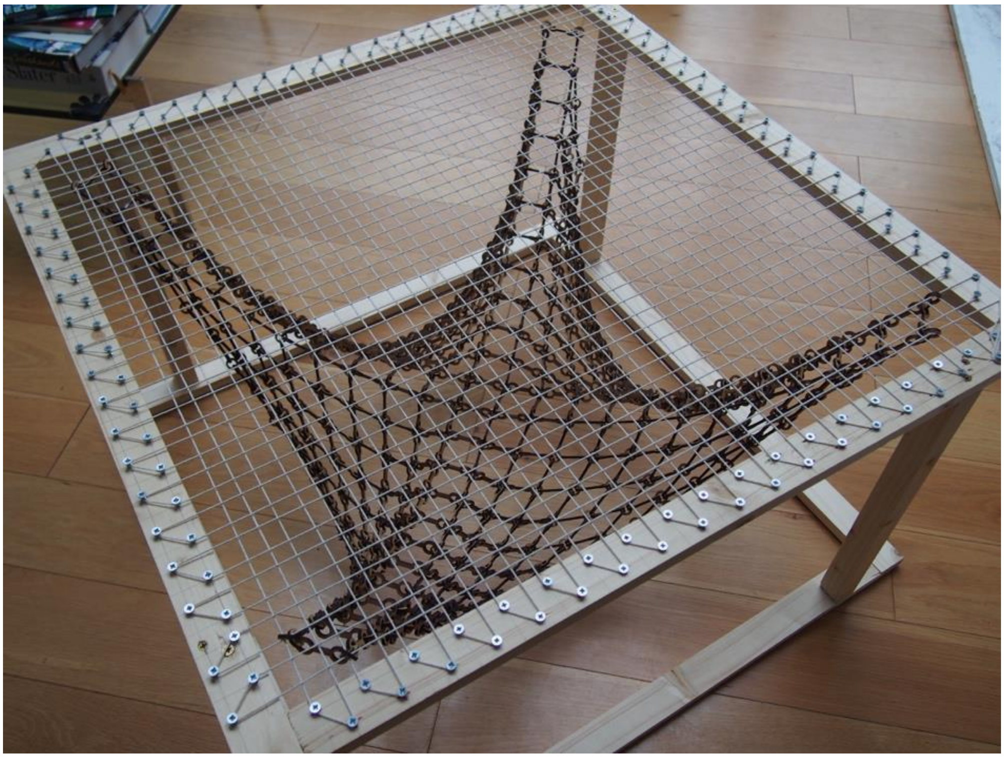


Fig 6.11 top: Hanging net laid flat at 5cm grid centre to centre. bottom: Hanging net deforms imto a shell shape when restrained at the four corners.

Fig 6.12 The deformed hanging net describes the deformed positions of a gridshell which could be constructed with the same grid dimensions.

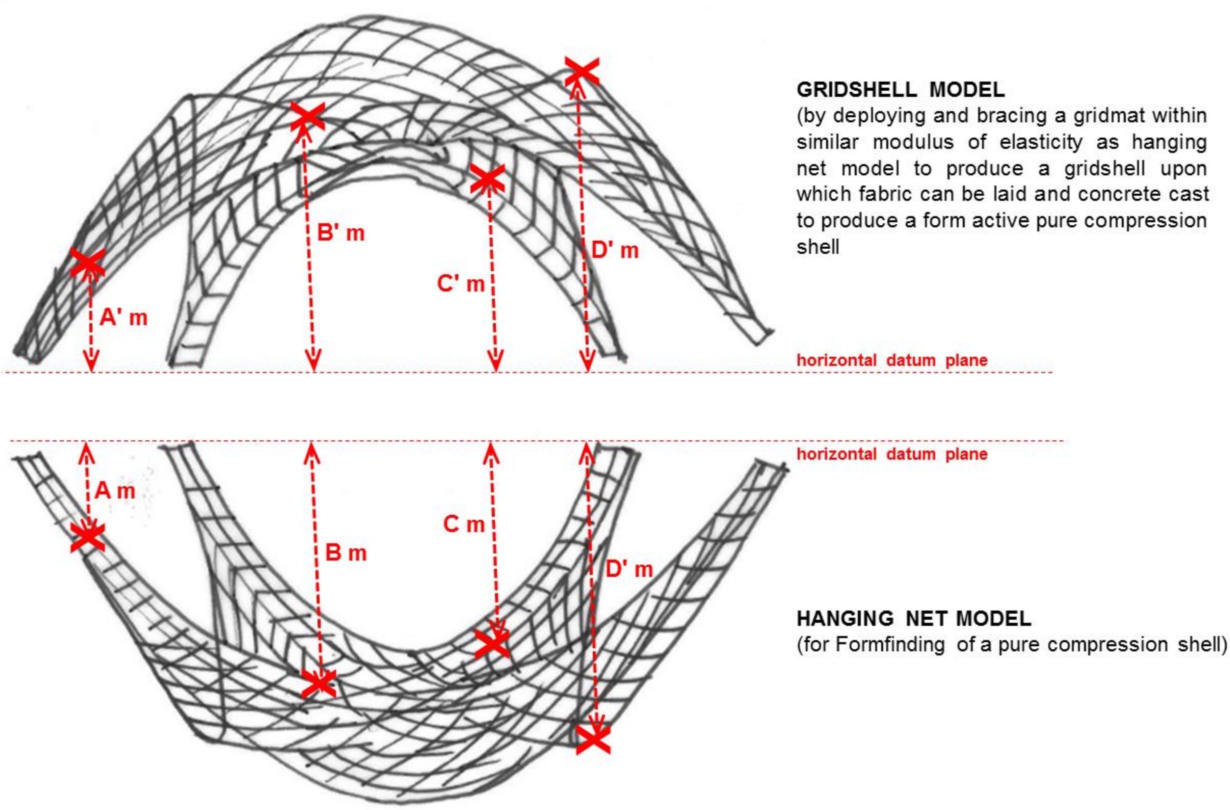


Fig 6.13 From the same gridmat, proper shells are easily designed to respect the elastic ratio of the materials in question.

As the hanging net is suspended at points, forms pertaining to pure compression condition results. In the first example, the four corners of the grid net were restrained to form a four-groined vault (fig. 6.14).

These geometrical information i.e. x-y and z co-ordinates at each intersection of the grid-net can be translated into an inverted gridshell of the same grid-size to produce a formwork upon which fabric is covered and concrete applied over. Referring to fig. 6.13, the location of each intersection on the grid-net can be transferred and scaled up to create a three-dimensional compression formwork for concrete pour. The grid-mat will need to be braced, adjusted and rigidified to produce a shell of the exact inverted geometry of the hanging grid-net.

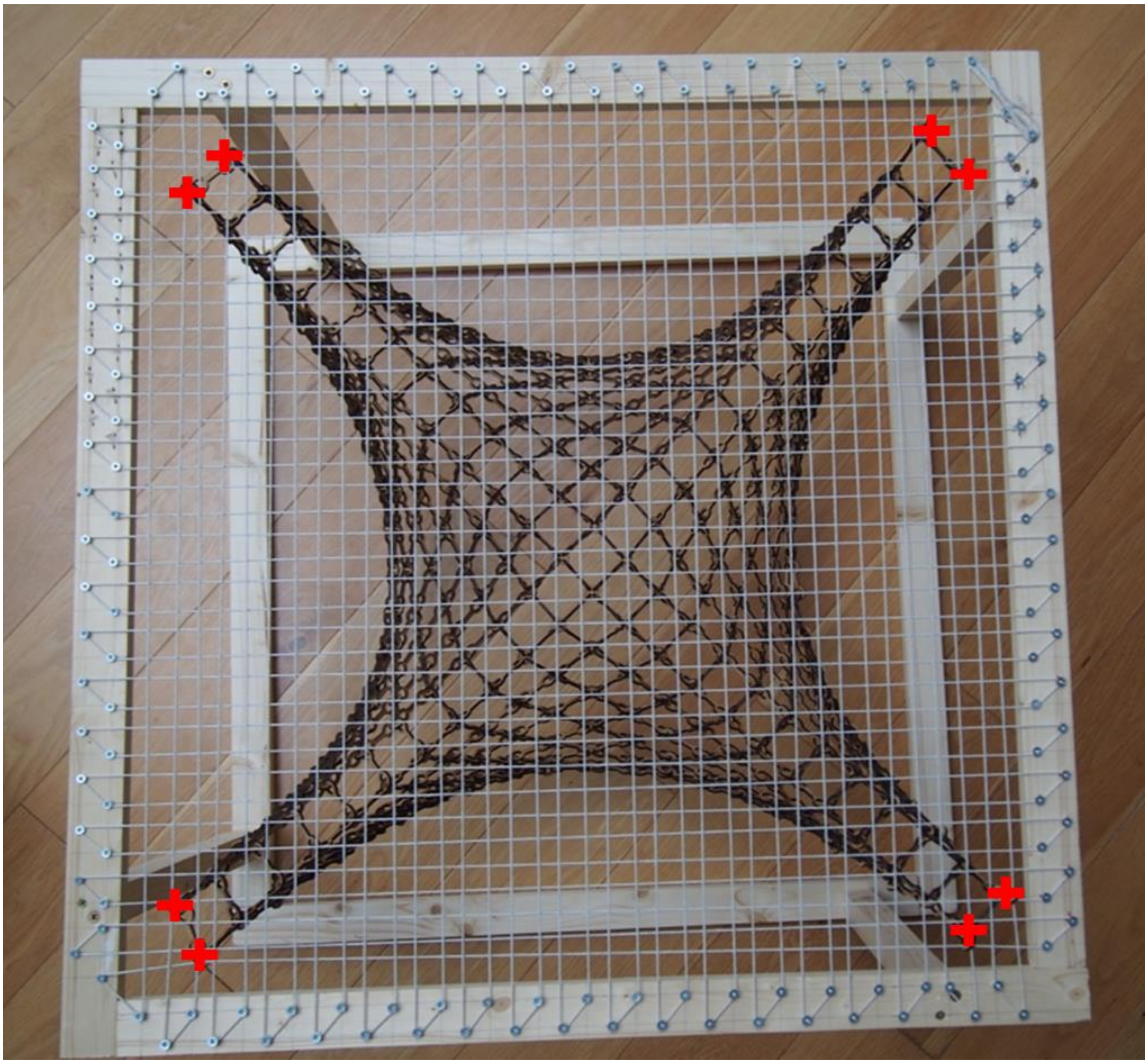


Fig 6.14 A plan view of the gridmat suspended within the frame. Restraint points are highlighted in red.

Variation 2

The reconfigurable nature of the grid-net resides in the manner by which the gridmat changes when it was suspended at different points.

A further exercise to reconfigure and vary the shell shape is trialled on the same grid-net. In this instance, an asymmetrical shell was made by suspending the shell from three main positions on the support mesh. Instead of suspending at points, the gridmat was restrained at five regions- four points and one lined edge.

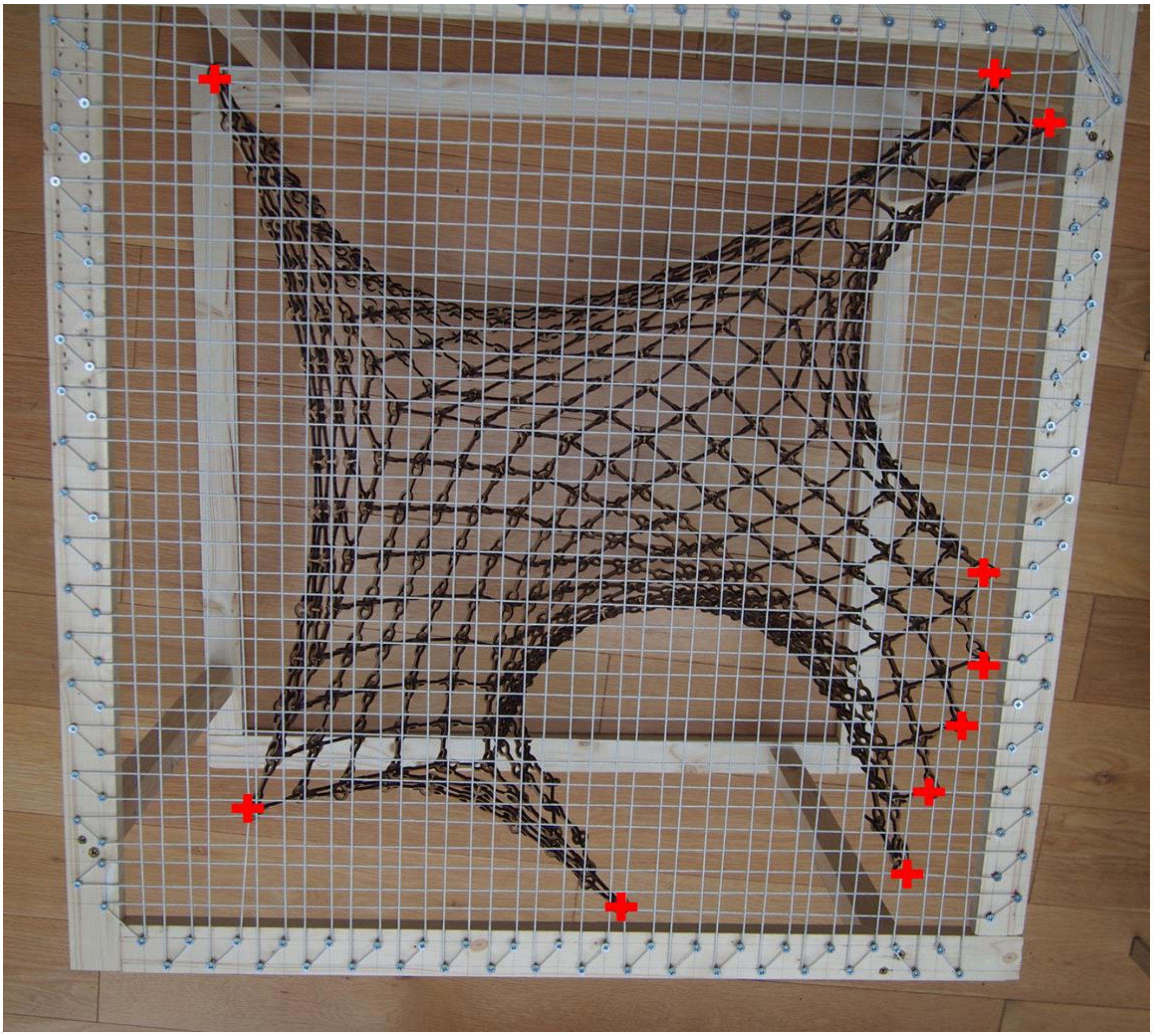


Fig 6.15 A plan view of the gridmat suspended within the frame restrained at points as described.

The deformed grid-net restrained at different points produced a different form accords with tensile forces. Visibly, a different undulating geometry can be achieved using the same grid-net. Of particular interest to the designer is their use as an interactive tool to understand the scale of spaces in relation to building programme. Illustrated conceptually, in figure 6.16, the three-dimensionality enables the designer to see, and appropriately adjust the grid-net to design form-active structures to contain specified building functions. Importantly, this tool allows the designer to develop an intuition to design shells to specific conditions such as solar orientation to design environmentally responsive structures with opening edges that addressed views and shading from the sun.

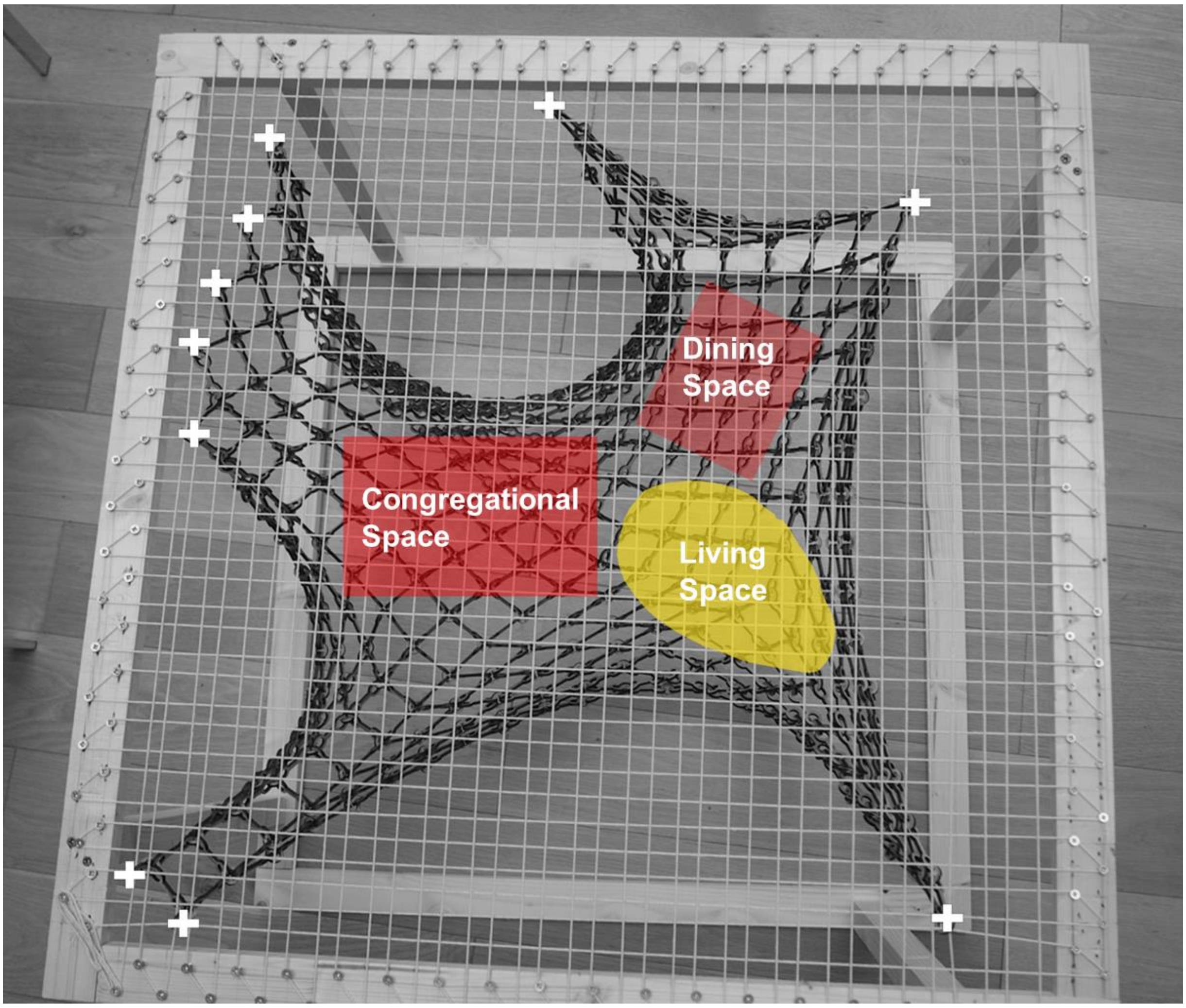


Fig 6.16 Being able to see the shell allows the designer to visualise the iplications of building function positioning.

When inverted and translated into a gridshell, the form can be transposed and scaled up into a gridshell formwork for supporting fabric onto which a thin layer of concrete can be applied to create a concrete shell.

Fig 6.17 Form variation of the same gridmat creates an opportunity for the designer to use as an interactive tool of design.

Further variation of forms can be adjusted by changing the grid-net edge pattern through removing sections of chain links. It offers flexibility and configurability opportunities for the designer without being distracted by structural efficiency. This gives the designer control and a large degree of structural intuition.

Grid net, edges, restraining points can be investigated further.

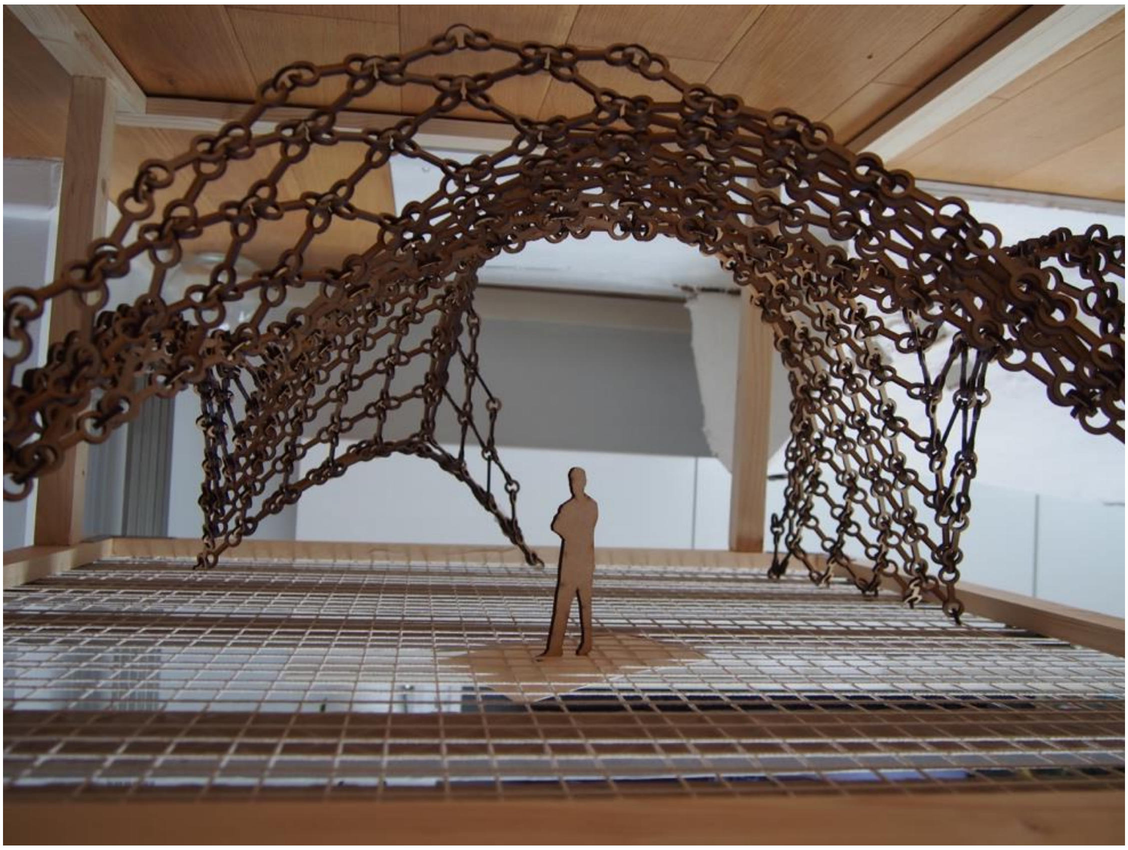


Fig 6.18 A suggestion of the spaces that can be form when the shell is inverted from a hanging net into a gridshell of the same geometry

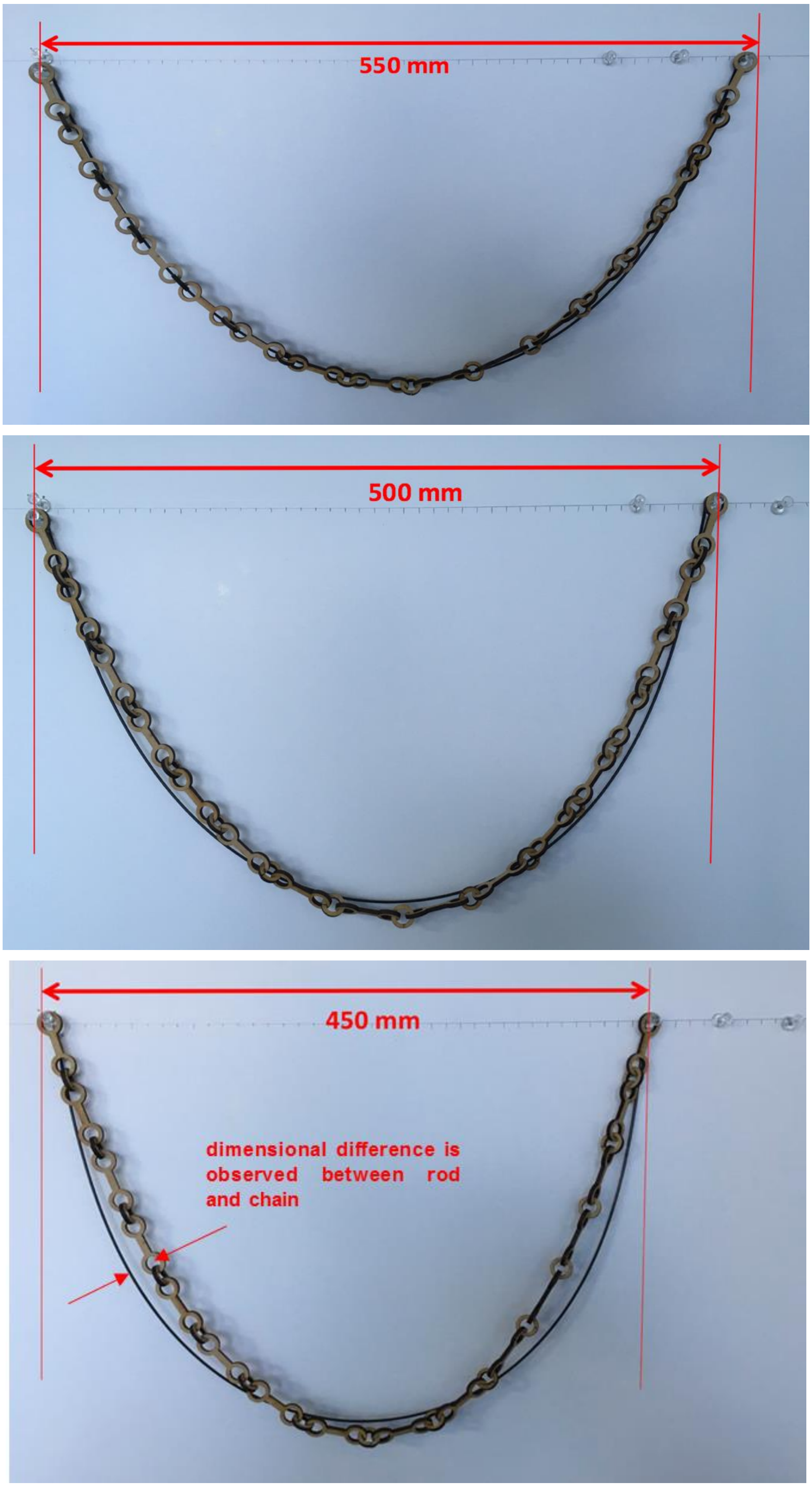


Fig 6.19 A 2mm diameter gfrp rod and a hanging chain (maide from mdf) both 750mm were subtended between points to observe the distance from which the two curves describe different geometries. The dimension is found to be 500mm.

This system is restricted to the ability to translate hanging chain geometry into a gridshell geometry. The suitability of the material is governed by the geometrical response to bending without fracturing gridshell members. For the exercise, shape responsiveness of both hanging chain and gridshell material 2mm GFRP rods are tested.

The hanging geometry will be inverted through the deployment of a corresponding gridmat of the same grid-size. Upon sufficient bracing, with fabric being laid across the gridshell, concrete can be applied. Afterwards, the gridshell can be unbraced and released for be re-use.

Referring to fig 6.19, a difference between the behaviour of the 2mm glass-fibre rods and hanging chain is observed. To investigate the limit upon which the rod begins to deviate from catenary shapes, a rudimentary test was carried out. In this test, a rod and corresponding hanging chain of 75cm were restrained from the same two end points. The free chain and bent rod described the same catenary curve.

To determine the accuracy of the model, material tests are carried out for each scenario. Both restraint points moved closer towards each other in 5cm increments along a straight line until a difference in geometry was noticed. The curved geometry deviated at restraint point distance of 50cm, giving a ratio of 50/75 i.e. 2/3. With the longest diagonal dimension of the square mat at 75cm, a maximum drape of 50cm (meaning an inverted gridshell height of the same dimension) would be achievable for the glass fibre rods to create a corresponding gridshell as a rule of thumb.

These dimensions are specific to each form-finding model.

Discussion

This preliminary method of designing concrete shells is useful for the designer as it can result in efficient shell forms informed by gravity intuitively. However, they are limited by the elastic behaviour of the gridshell material e.g. glass fibre polymer that replicates the hanging net.

This method describes shells in pure compression. The hanging net method was used by Heinz Isler for form-finding efficient shell shapes. However, these curves had to be transferred onto timber formwork. Compared to Isler’s method, the gridshell translated the hanging net model readily.

At the beginning of the design process, this method sought to provide an understanding of shell forms non-mathematically i.e. without computational form generation or digital analysis. By using a gridded hanging net that corresponded to the gridmat in search of shape that is effectively acting in complete compression imparts three key benefits:

- Firstly, the designer can understand the effects of changing shell form architecturally related to spatial planning. The hanging chain model could serve as a visual and three-dimensional aid to understanding the interaction between shapes and vertical forces.

- Secondly, the points of intersections of the hanging chain can be translated directly onto the final points on the complete gridshell provided the elastic behaviour of the gridshell material is respected. The gridded nature of the co-ordinates of a hanging chain net corresponds to the intersection of the gridmat, giving rise to locating of specific points in x- y- and z- axes.

- Thirdly and most fundamentally, by knowing and using this method, the architect who is approached by the client, may be able to suggest concrete shells as a possible architectural solution. Through understanding the structural principles of proper/ pure compression surface structures, the architect would not initially discount surface structures (which have many advantages), but may suggest them, appropriately to exploit their architectural offering.

It is important to note that not all shells are designed this way. Eduardo Torroja did not design the Zarzazuela amphitheatre roof by using hanging chains. Informed by paper card models experiments, it required reinforcement loops to counteract bending and tension stresses within the thin concrete.

It is suggested that small scaled hanging models of gridshells can be useful tools for the architect to design and develop a scheme non-mathematically at the initial design stage, then elaborated with/ by a structural engineer at a later stage. This offers a hands-on, direct, tactile and intuitive way of designing when compared to designing on the computer.

Crucially, this process engages various parties in preliminary discussions. It could remove barriers to erode the uncertainty of architects from considering shell forms in the first instance raised by Tang,

2016. Architects, usually the first point of contact by clients, may be deterred from curved shells by their complexity of geometrical and structural analysis. It may be possible for the physical model to erode this uncertainty as evidenced in the 2011 Hallam University gridshell workshop where the model was instrumental in working out the construction stages.

6.3.2 Gridshells as Form Making Tool (Improper Shells)

Deployable gridshells as formwork for *improper shells*.

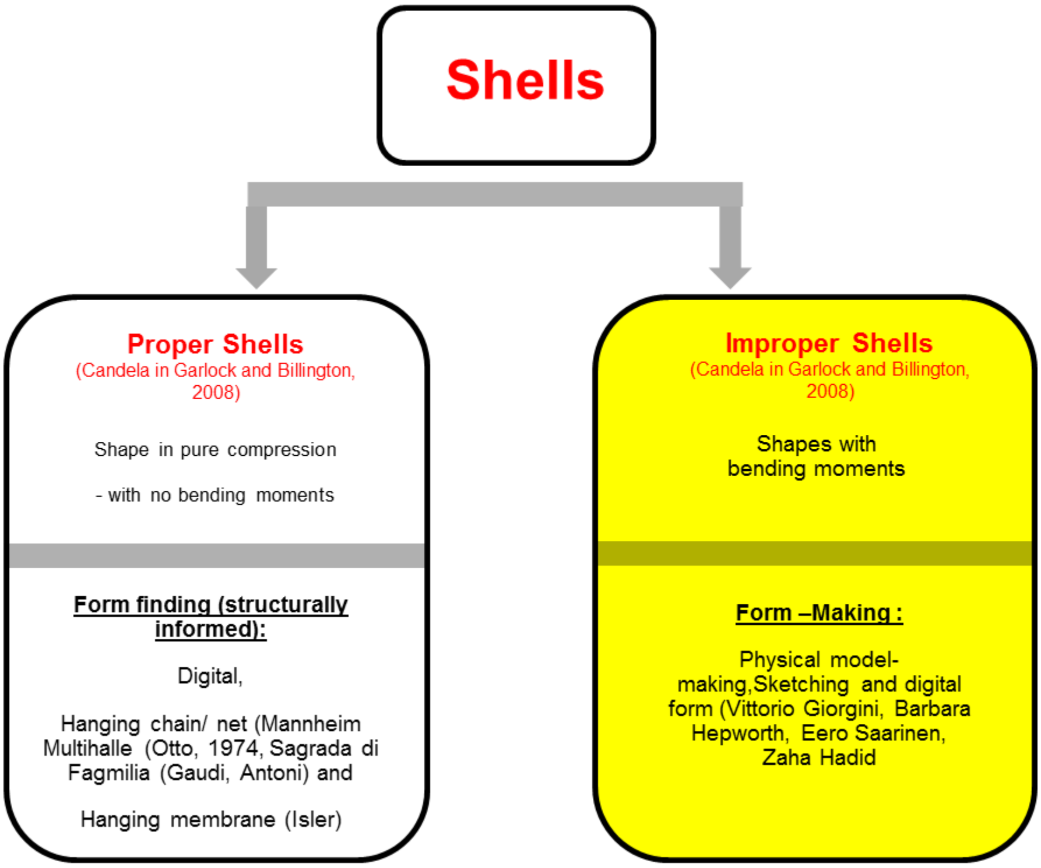


Fig 6.20 A suggestion of the spaces can be formed when the shell is inverted from a hanging net into a gridshell of the same geometry

Deployable gridshells as formwork for im*proper shells* (shapes with bending moments)

Formfinding using earlier methods helps produce (proper) shells with structural reasoning. However, their appearance and shaping may not cater to the aesthetical needs of the designer. Deployable gridshells aid the design of shells which do not prioritise structural principles. Although these structures are not "pure" in the structural sense, they offer the opportunity for the designer to experiment initially with shapes and forms in a qualitative way, liken to how architects use sketch models to test out ideas at design project infancy.

The principle is based on active bending by a gridmat to produce a doubly-curved three dimensional shell conducted during the construction of the 2011 Swells structure where deployable gridmats can were deformed from a flat mat to a three dimensional doubly curved shell by compressing parts of the shell together or pulling them apart. This method induces compression, tension and bending forces within the surface, resulting in what Candela refers to as an improper shell. Qualitatively, the result showed large areas of weakness subjected to bending moments. Areas of contraflection also resulted in unstable behaviour manifested in the highly deflective nature of the shell raised in Chapter 5.6.3.

To further demonstrate the use of gridmats to produce gridshells, a test was set up to investigate this ability more objectively.

Test Model

A gridmat measuring 300mm x 300mm with a 45 deg grid was made with a grid-size of 20mm was constructed from thin 1.5mm thick past card cut into 5mm strips and pinned together at the intersections.

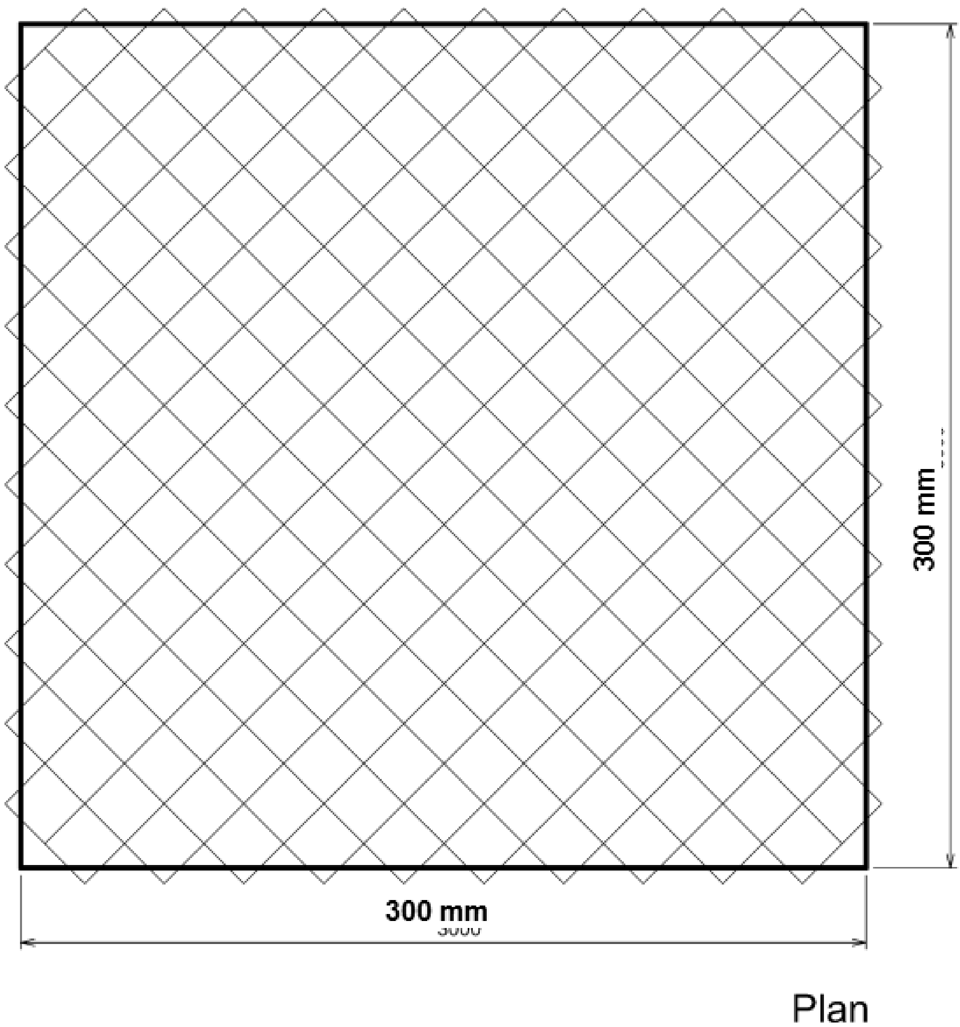


Fig 6.21 An exercise where a paper “improper shell” is created from a paper model.

A series of deformation was tested by deploying this flat mat:.

Variation 1

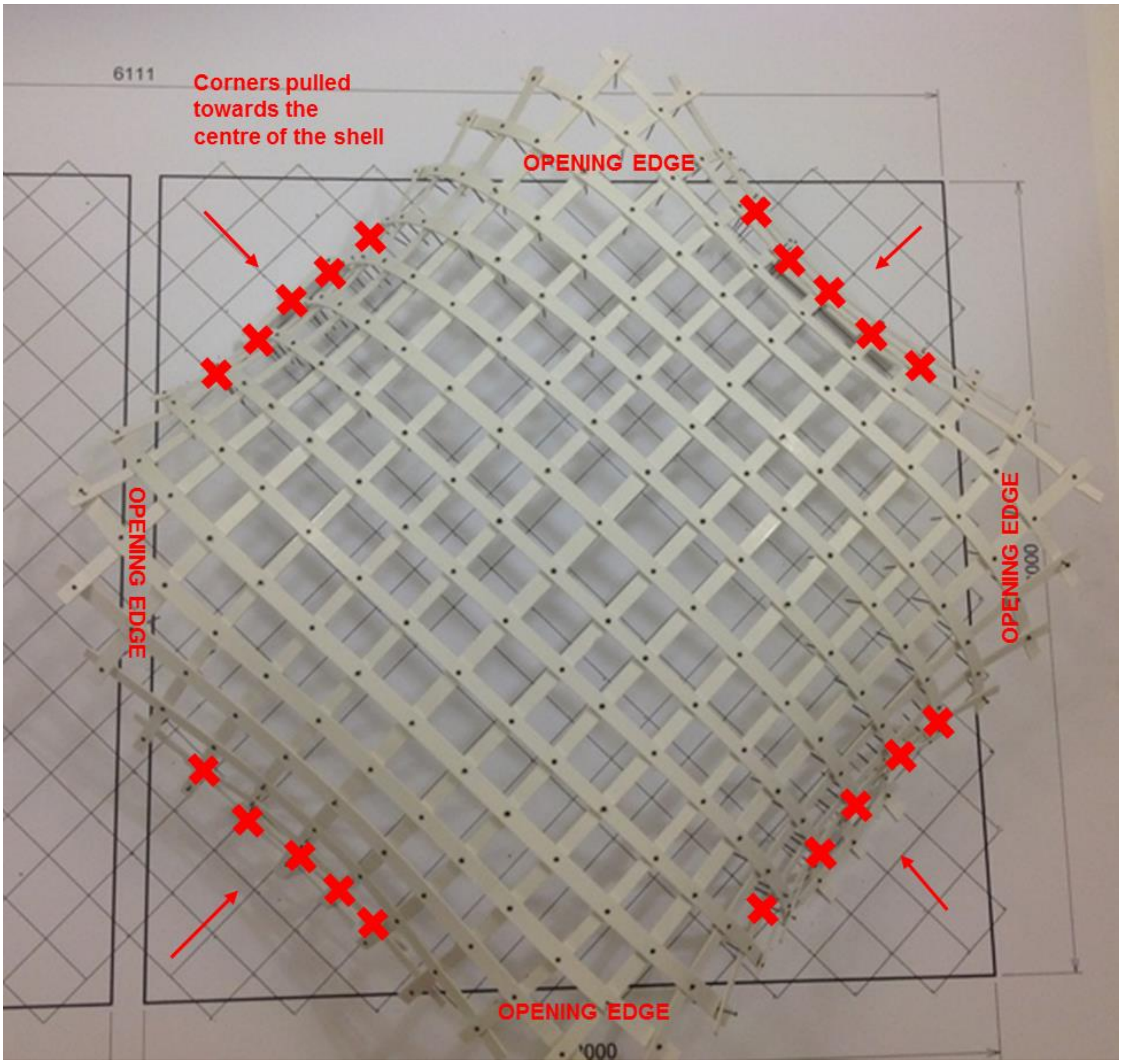


Fig 6.22 An exercise where a paper “improper shell” is created from a paper model. Plan view of variation 1.

The four corners of the square gridmat were pulled towards the centre of the gridshell and restrained by pinning them down onto the foamboard. This results in a simple synclastic shell with four opening edges at the corners as illustrated above. The shell was symmetrical. Further inducement of curved geometry changes is possible as the grids can be pulled together or pushed apart.

Variation 2

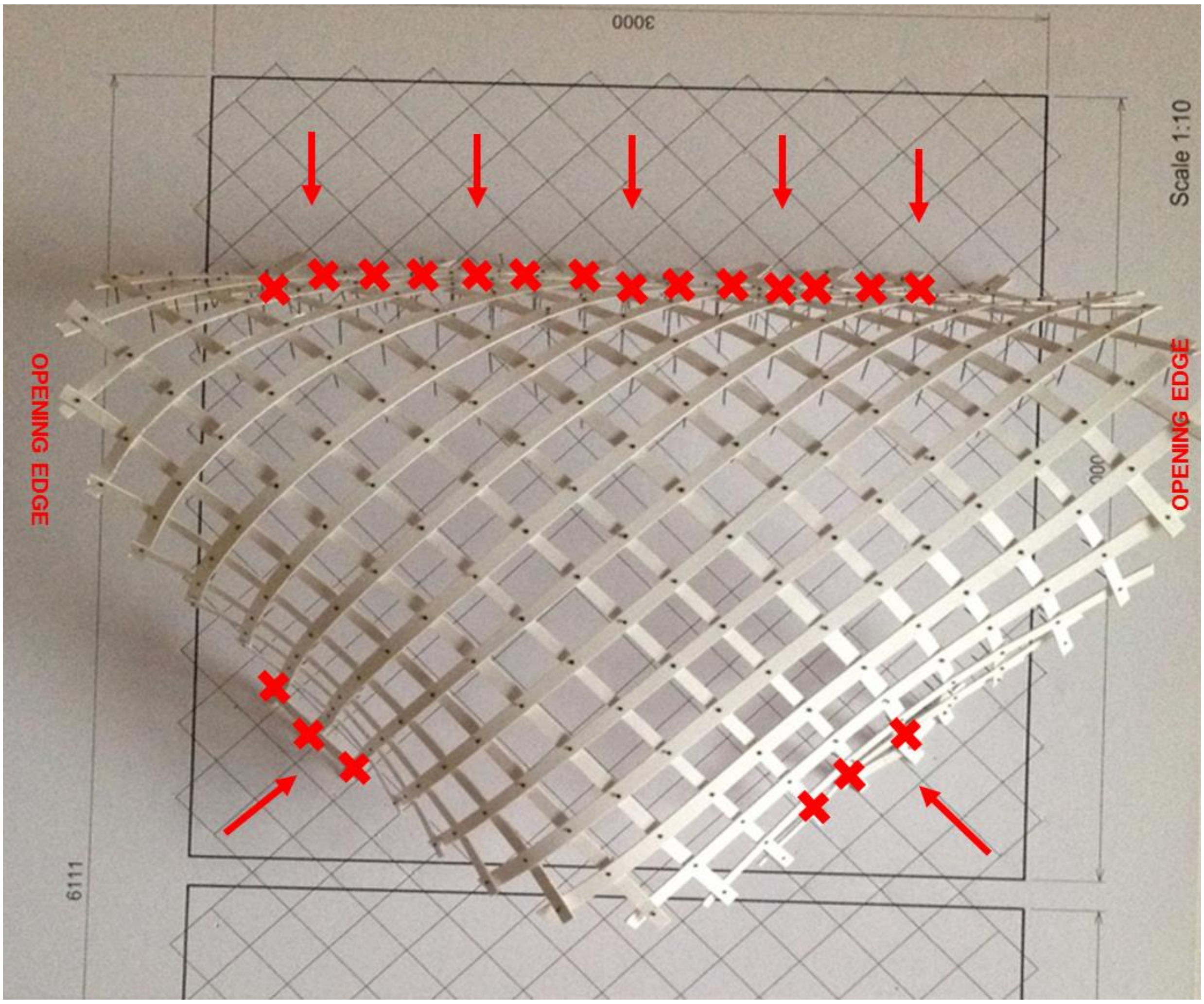


Fig 6.23 An exercise where a paper “improper shell” is created from a paper model.

Without modifying the gridmat, the pinned restraints at variation 1 was removed at the top 2 corners and the entire edge was moved towards the shell centre and restrained. This results in two openings at opposite sides.

Variation 3

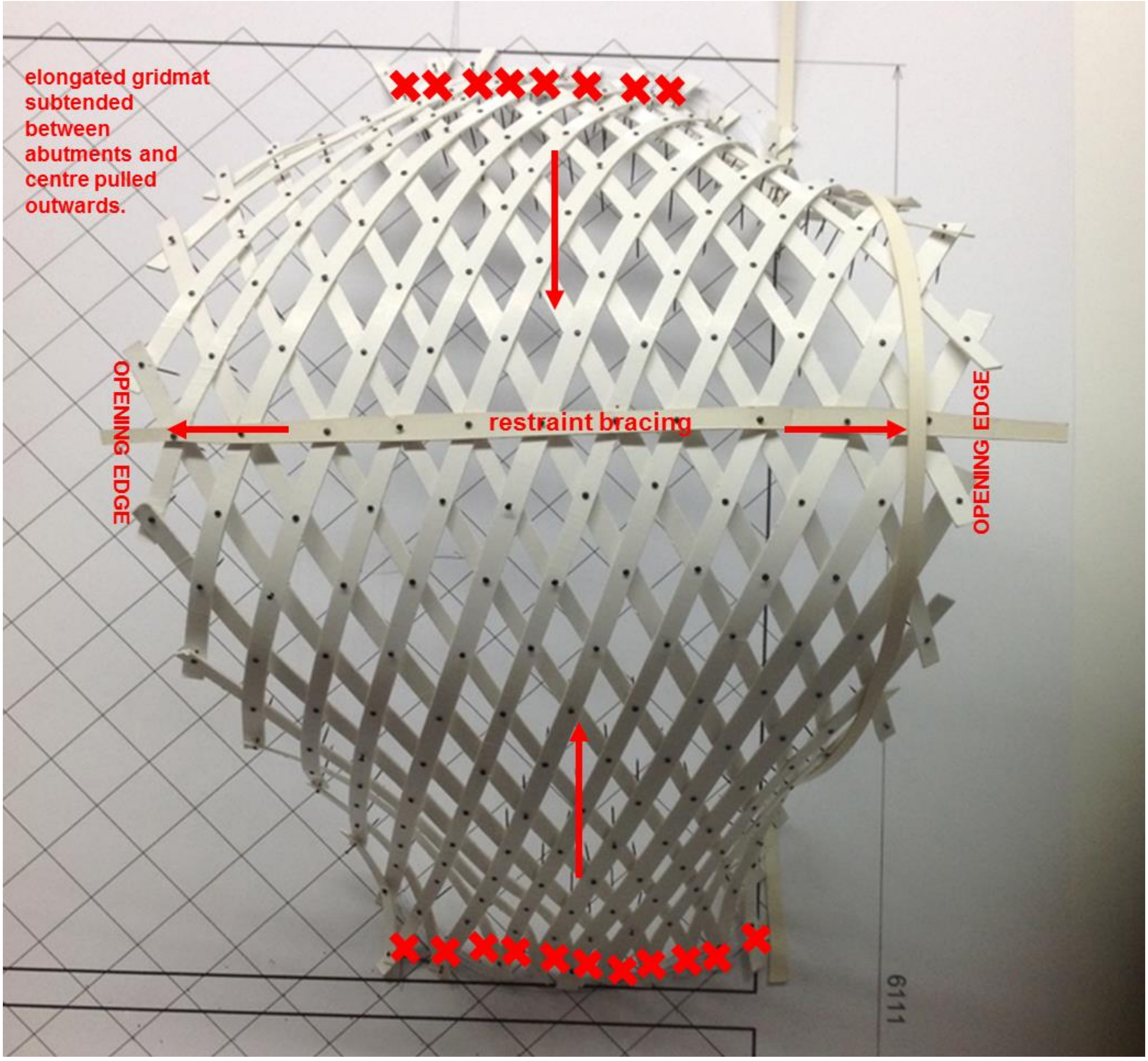


Fig 6.24 A variation of actively-bent shells can be form-made from an actively bent gridshell from the same gridmat. From the same gridmat, improper shells are designed by manipulating the gridmat by tension or compression to create double curvatures.

All pin restraints of the gridmat were removed to resume the original flat state. For this variation, the entire gridmat was pulled to extend along the direction of deformation. It was then restrained onto the pin board at one end. The other end was pushed towards this restrained edge to produce an arch. To induce stronger double curvatures, a restraining bracing was secured at the middle section of the arch by pushing the grids apart to widen the arch apex.

The same gridmat has therefore produced at least three re-configurations to be stabilised and braced further. These possibilities are at the beginning stages of form-making which required further discussions with engineers to fine-tune and be adjusted through structural analysis to understand this technology better.

Variation 4

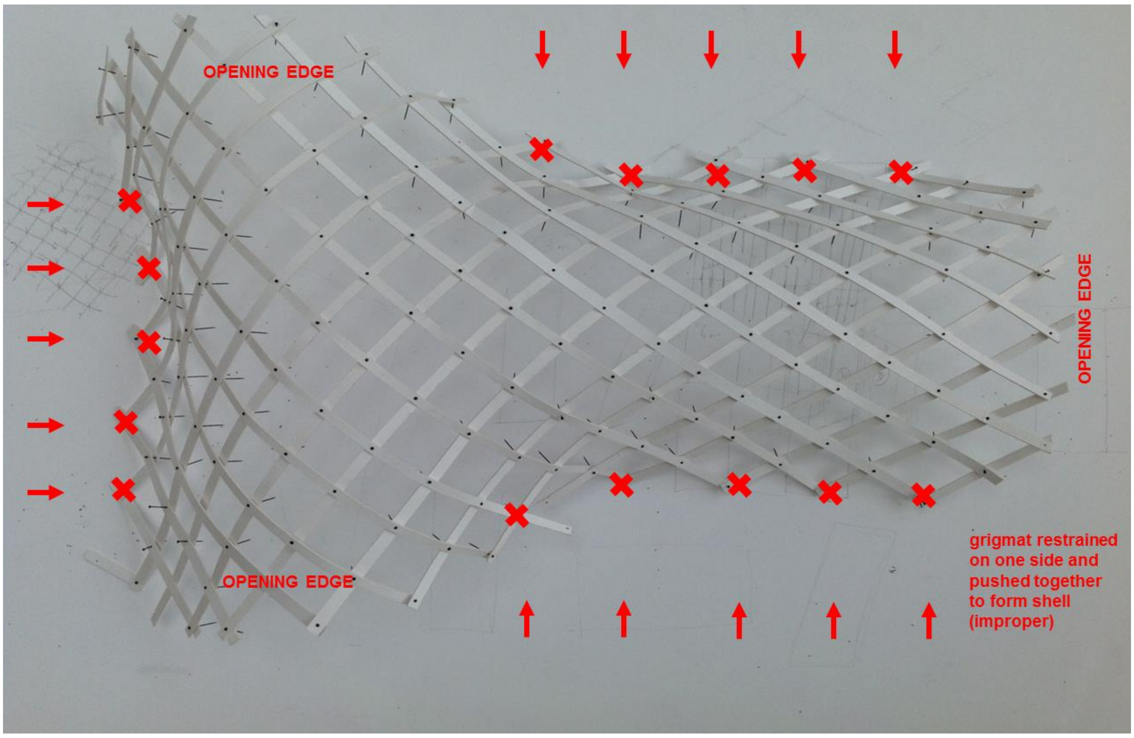


Fig 6.25 Actively bent gridshell variation 4.

By elongating gridmat, and pulling the gridmats, heights and dimensional changes can be made. Variation 4 above is a permutation of Variation 2 with a different proportion to accentuate one of the arched openings giving it dominance, but with lowered height in this region.

Variation 5

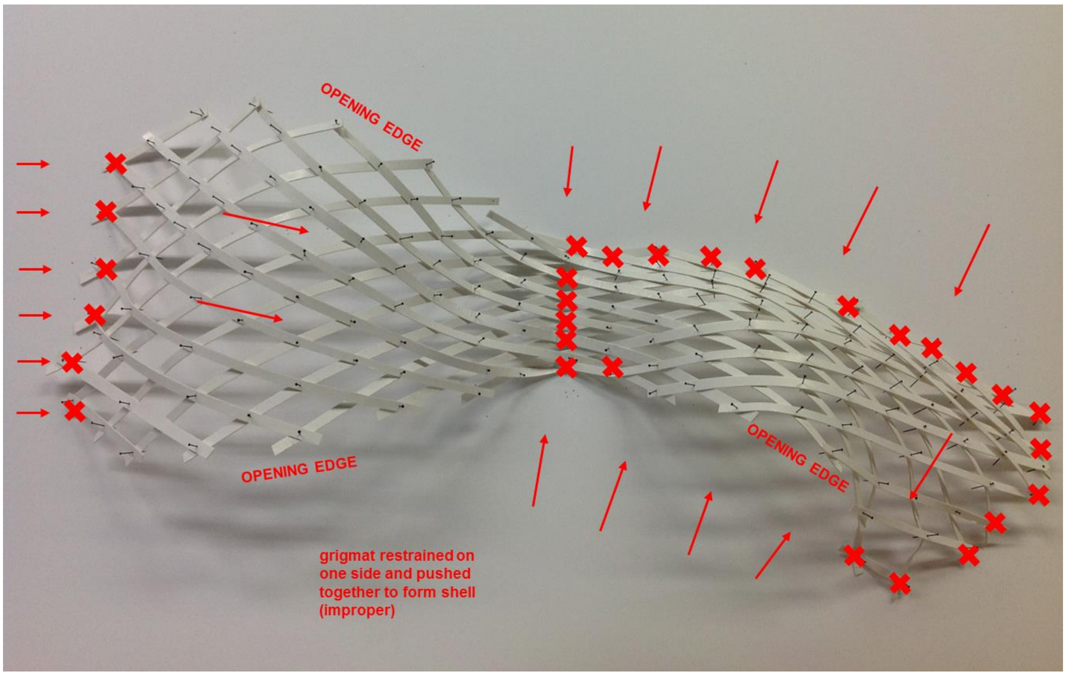


Fig 6.26 Actively bent gridshell variation 5 displays an organic free-form.

Deformation exercises can also produce more expressive and asymmetrical shells. By varying boundary conditions on the foamboard, different geometries, which are not draw-able can be created. These gridshells can function like sketch models to help architects think and plan the spaces.

All these doubly-curved shell shapes arose from a single gridmat measuring 300mm by 300mm on plan. This process could be developed further by tailoring the gridmat to generate shell shapes with sufficient height and/or desired in-plane stiffness.

6.3.3 Discussion

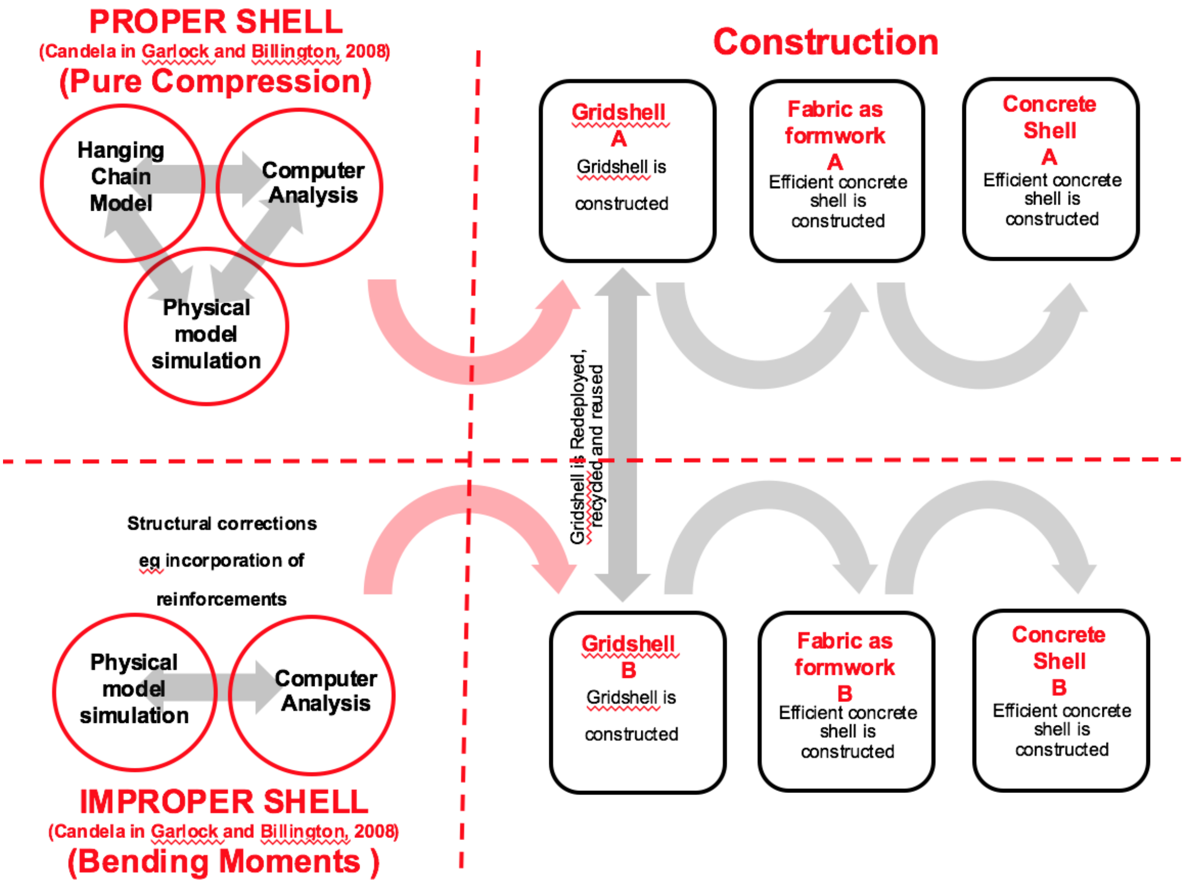


Fig 6.27 Consideration and Processes of Shaping in Proper and Improer Shells.

Previous illustrated variations showed how deployable gridshells could be used for both form-finding in *proper* compression shells, and form-making of *improper* shells. Using a hanging grid-net, compression shell forms are form-found and be translated into a gridshell. These gridshells can then be covered with fabric and concrete is then applied over.

On the other hand, deployable gridmats can be used to generate shapes that focussed on designers' need to visualise spatial implications/ requirements of the shells, rather than be structurally motivated. As demonstrated, this is closely associated with the construction process, especially in terms of deployment sequencing.

Fig. 6.27 summarises the processes in these two shell types. In both cases, the physical model could initiate a discussion with the engineering specialist. The use of the same deployable gridmat can be used in both proper and improper shells, suggesting a highly adaptable system in the design and construction of concrete shells.

6.4 Stereogeneous Process (Manelius, 2012)

The hypothesis sees a construction process that combines three process-focussed technologies: concrete shells, fabric formwork and deployable gridshells. As seen, the final artefact (resultant concrete shell) expresses processes and their synergies. The ease of design and preparation of formwork and concrete cast is key to the success of all concrete shell constructions.

This intrinsic relationship between formwork and concrete shells is evident in their appearance. Expressed as imprints of the gridshell and fabric support, this appearance addresses the concerns of Miguel Fisac (Chapter 4.8.1) who fought against the tectonic of concrete borrowing qualities from prismatic timber formwork and not owning qualities of itself (Pedreschi 2012 at ICFF, Bath). The hypothesis suggests this appearance as a auto-biographical result reflecting material and process.

The idea of stereogeneity was a coined term by Manelius (2012) to discuss this notion, she explains the term:

> *"which attempts to embrace the duality of, on the one hand the experienced, sensed qualities of a cured concrete structure as material and, on the other hand, those almost metaphysical traces of becoming that may be the most poetic feature of concrete. The term stereogeneity comes from the Greek word stereogenes. It consists of two words: stereo, solid, and genes, derived from ginomai, the procedure of becoming or to begin to be. Cured concrete then is stereogeneous: it is solid but as the word indicates, has become solid through a number of processes beginning with a liquid state."*

Concrete's stereogeneous quality is therefore crucial to the building of shells. Being viscous to begin with, it readily flows into moulds (fabric formwork acting as surface moulds, supported by a temporary gridshell) which defined their appearance and thereby structural behaviour.

In this scenario, concrete cures to become thin structural surfaces. The idea of an ephemeral liquid transforming into permanent solidity is intriguing, both technically and poetically. The spirit of this research idea strikes a chord with Manelius's concept of stereogeneity.

Therefore, the understanding of the three technologies (concrete shell forming, fabric formworks and deployable gridshells) which imbues the notion of changes needs emphasis.

All preliminary experimentations to this stage points to supporting the use of deployable and actively-bent gridshells as reconfigurable, intuitive and reusable concrete shell formwork. The question of how well the gridshell can deploy and actively-bend lies firmly in the results of tests, designed to verify and improve formwork design, erection and casting processes.

6.5 Points of considerations of the hypothesis:

- Design process may require specialist design techniques (e.g. knowledge of sophisticated computational form-finding software) and this deters architects from applying shells in their design proposals. Although materials are cheap, the system design requires designers to understand all three technologies in construction, aesthetic and structural terms.

- The behaviour of formwork during the casting period needs consideration. Deflection of the formwork may result in a shell shape that is different from the original gridshell designed. With digital parametric tools used by specialists, shell sizes and grid sizes can be changed easily as well.

- Degree of gridshell deflection will impact on the geometry and therefore structural behaviour of concrete shells. It is expected that gridshell formwork would be highly deflective whilst concrete is applied onto the formwork. Deflection behaviour requires understanding and be taken into account in order to create a formwork that is stiff and resistant to the casting process.

- Scale issues and labour requirements
  The size of the gridmat is an interesting questions - how big can this gridmat go and still be manageable enough to deform? At a larger scale, it may not be feasible to manipulate this. Grid sizes impact on manoeuvrability, degree of labour input and/ or the requirement of specialist equipment such as expensive cranes.

- Steel reinforcements have been added to concrete to alter material strength. Torroja's steel loop reinforcements for La Zarzazuela Hippodromo, Madrid (1935 in Chapter 3.3.4) were designed to enhance structural performance concrete shell. Steel bar reinforcements were also used where tight curvatures exist (West, 2016). Polypropylene fibre reinforcements or steel staples can be added into concrete mixes to increase their tensile strength.

- Edge details need to be designed carefully. To provide additional stiffness and express shell thinness, Isler made use of the upturned free edge to express this. These aesthetic considerations inform the way thicker insulated concrete shells can be detailed at their edges to impart an illusion of thinness, should the designer wish to do that. This is a key element that affects the impression of thinness.

- How the shell meets the ground is an important point to consider. This is especially important as interfaces between deployable gridshell and in situ concrete abutments need to be designed carefully to remove gridshell safely and easily away from the concrete cast.

- Openings and light penetration. How light enters and heat escapes are crucial to the effective design of shells to meet the needs in an environmentally conscious century. In surface structures, as openings in the shell surface weaken the structure, these openings must be considered carefully with the engineer. The grid pattern of the gridshell formwork may offer opportunities to locate these openings to create a climatically-controlled internal environment.

- Accuracy and Precision
  How concrete is applied onto the concrete shell is important as deployable gridshells can be unstable. How they deflect during casting may affect geometry precision, impacting on structural strength. The process of concrete loading is an important factor as it introduces additional forces which deform the gridshell formwork. Movement of the flexible gridshell during the process of concreting may result in a shell which did not follow the exact designed geometry. When falsework scaffolding is to be minimised, due to the deflective nature during concrete loading, it may become necessary to use temporary props to stabilise the temporary formwork (ie gridshell) to ensure all key points in the shells are at correct heights.

- The sequence of concrete loading is an important consideration. For efficiency, large surface areas may require gunniting. Impact forces of gunniting will affect the accuracy and precision of final concrete shell. If the shell deviates from designed geometry, the morphological inaccuracy and construction imprecision will impact on structural performance and usefulness of the shells.

  As seen, the accuracy of concrete shell is dependent on numerous factors:

- How concrete is loaded: staged or phased loading and region sequencing.
- How concrete is applied onto the grid shell: hand trowelled or sprayed concrete
- How concrete is applied, especially at height, is an important question as the requirement of specialist machinery such as cranes and lifting equipment will increase cost.

Removal of the formwork needs careful consideration. Areas such as parts touching the ground in the *Swells* installation will need to be removed carefully or designed with a gap underneath the supporting gridshell such that the gridshell formwork may be removed easily in sections and moved as illustrated in fig. 6.28 to fig. 6.30. Designing concrete shells which takes into account of decentering is a major issue in systems design.

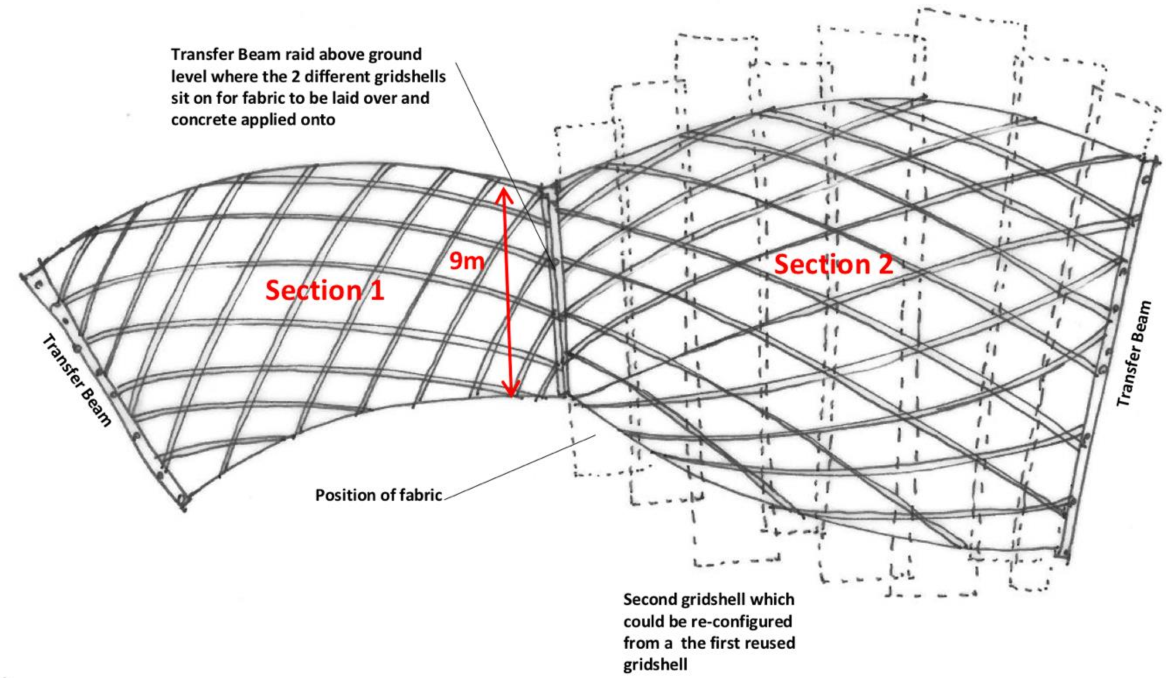


Fig 6.28 The swells will be divided into 2 sections.

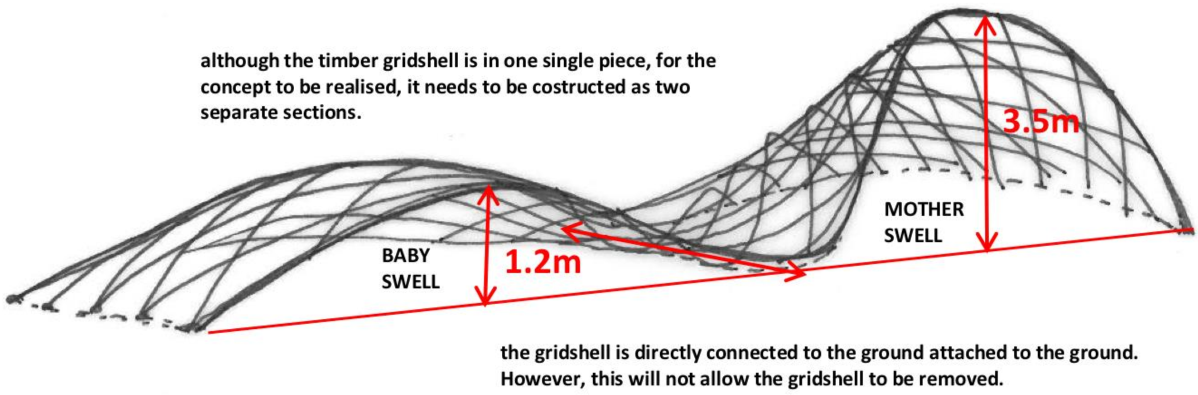


Fig 6.29 The existing timber gridshell with a central section resting directly on the ground will not allow the gridshell to be removed from underneath the concrete shell easily.

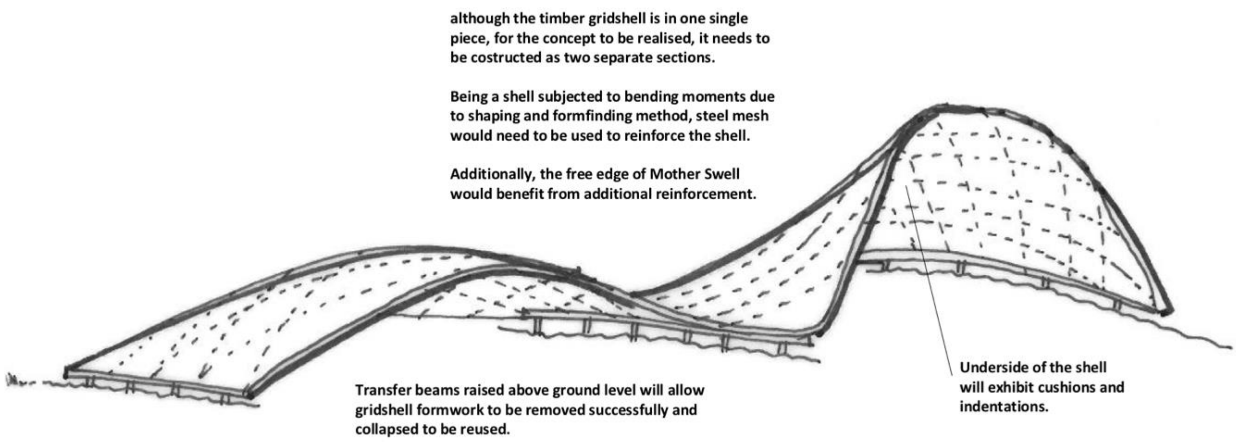


Fig 6.30 The middle section of The Swells sits on a transfer beam/ abutment designed to enable the gridshell to be removed from the complete shell from underneath.

- The bracing of the gridshell may be challenging, affecting labour requirements. The gridmat may be first constructed in the factory, then braced by hand on site to reduce time and cost.

Fig 6.31 Another mock up of a simple gridshell actively bent to produce simple double curvatures that allows concrete (modroc) to be applied to create a concrete shell. These figures give an impression of what the underside of these improper shells may look.

6.6 Ideas and Flash Experimentations (Benjamin, 2012)

The following section discusses a catalogue of Flash research inspired experimentations that explored this concept since the formation of the idea (chapter 2.6). This is presented in two parts- namely: A series of Concrete Canvas experimental constructions and further student workshop involving Concrete Canvas presented in 2013 (Tang, 2013). Concrete canvas is a thick fabric (as explained in Chapter 4.7.3) with cement embedded within the fabric thickness. When hydrated, cement is released and activated to result in a thin hardened shell surface. This material combines the benefits of fabric formwork and the casting of concrete shells and was explored through a series of desk-top studies and life-builds.

6.6.1 Concrete Canvas experimentation

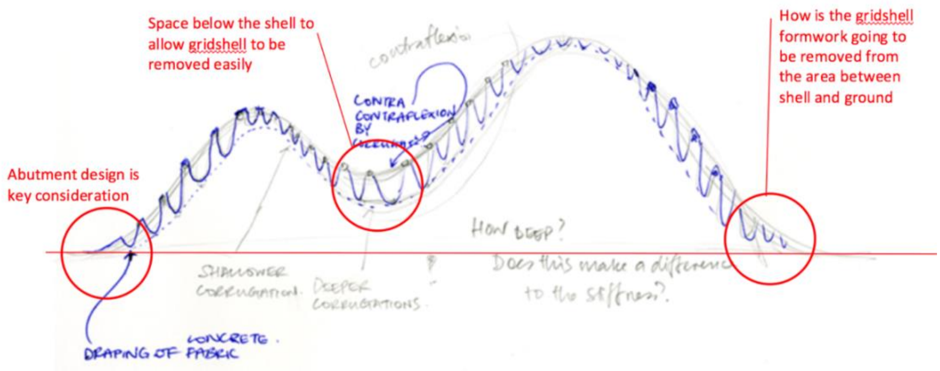


Fig 6.32 The idea of draping concrete canvas over a deployed gridshell was explored in terms of construction and aesthetics. Spaces below the concrete shell is an important factor of consideration in systems design for the effective removal of the temporarily braced gridshell without damaging the concrete shell and without damaging the gridshell as well.

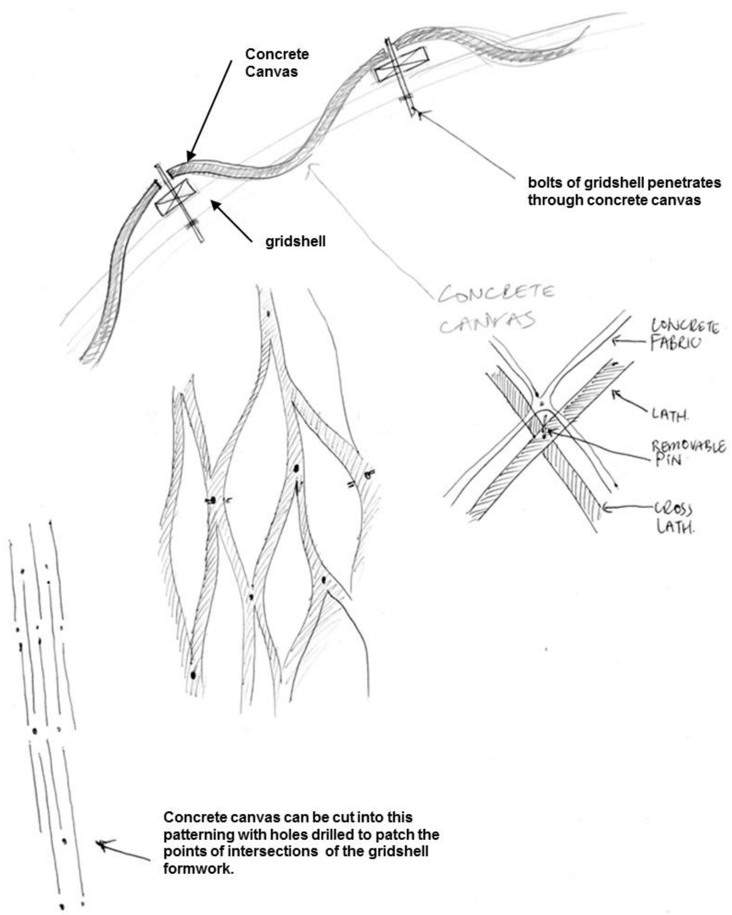
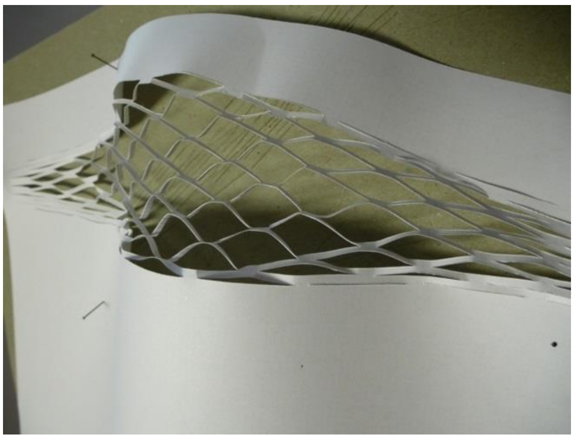


Fig 6.33 Spaces below the concrete shell is an important factor of consideration in systems design for the effective removal of the temporarily braced gridshell without damaging the concrete shell and without damaging the gridshell as well.



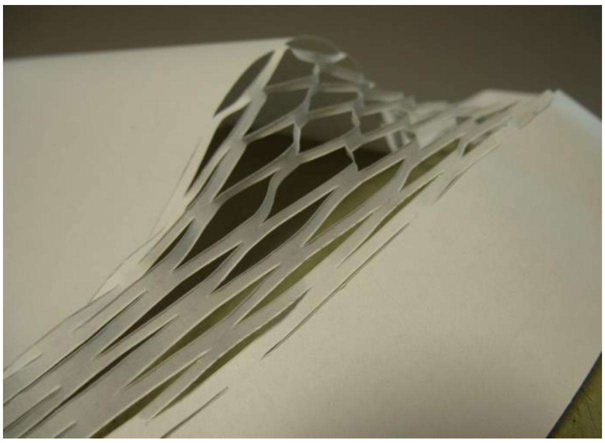


Fig 6.34 Scaled model mock-up of the use of concrete canvas forms the concrete shell. Slots were cut into paper that represented concrete canvas to generate a grid that corresponds with the grid pattern of the gridmat. When deploys/ stretched, the tectonic is expressed in the photograph.

To test out concrete canvas at full-scale, to eliminate decentring difficulties, fabric formwork was suspended from the gridshell. Although this created an interested form, the fabric was not sufficiently stiff when hydrated and hardened. Additionally, it was difficult to remove the gridshell from under the fabric formwork. As many cuts were made, much of the cement escaped through the cuts through the concrete canvas and reduced the cementitious nature of this material.

Fig 6.35 The actual concrete canvas was cut and connected to form a gridmat that matched the gridshell above

Fig 6.36 A mock-up of the use of concrete canvas to form the concrete shell. Slots were cut into the fabric to create a grid that corresponds with grid pattern of the gridmat. Although the shell corresponded to the gridmat , the shell did not work structurally.

6.6.2. Material Connections Student Construction Workshop, 2013

A student workshop entitled Material Connections, organised in 2013, experimented with the laying and casting of concrete canvas onto an actively bent and deployed timber gridshell. The dry concrete matrix fabric was laid onto the timber gridshell and subsequently moistened. After curing, the canvas became rigid and the formwork was removed. Without cutting up the fabric, concrete canvas retained the structural integrity and was stiffer than the previous experiments with concrete canvas displaying very interesting quality of aesthetics.

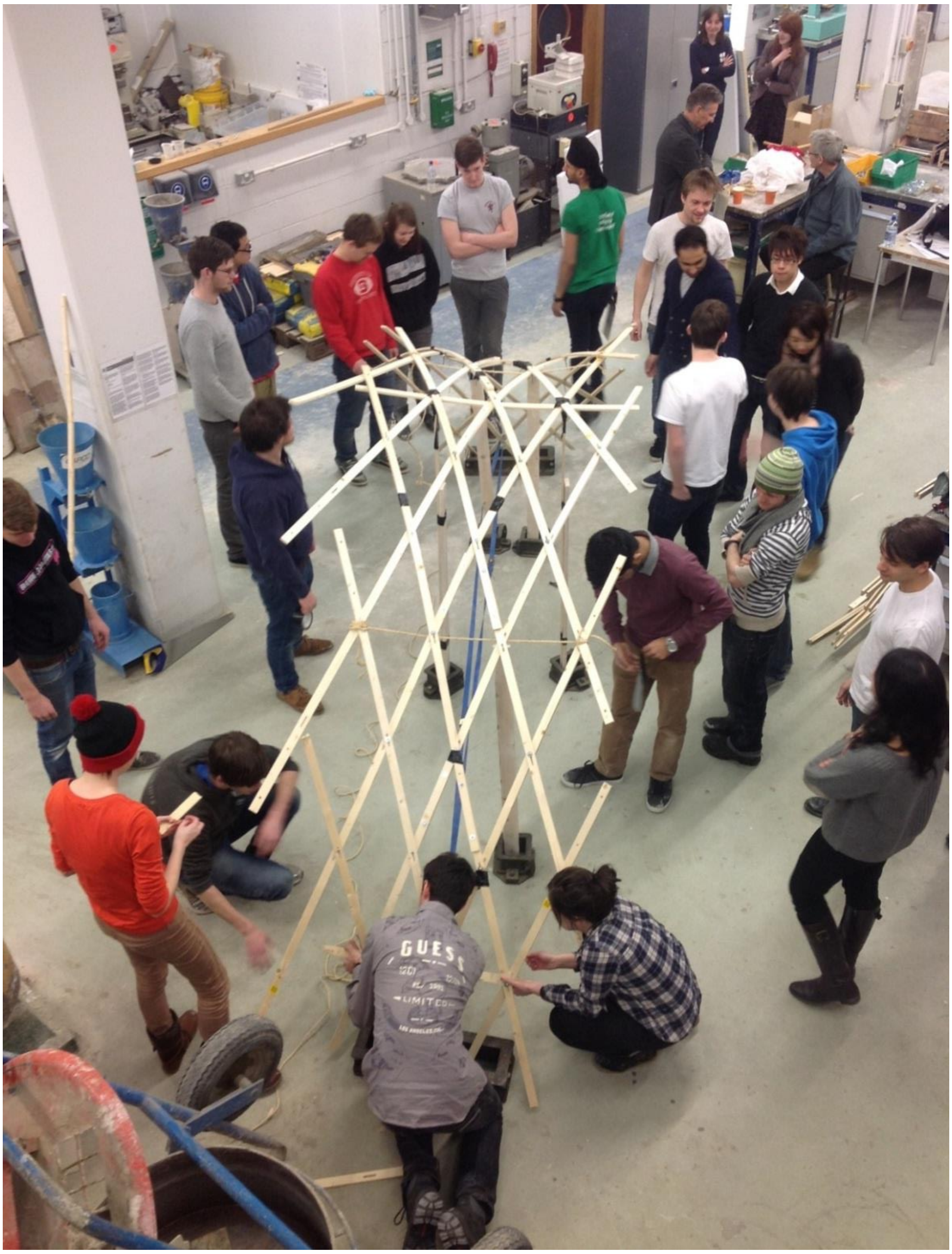


Fig 6.37 The deployed gridshell formwork was restrained by rope and supported vertically by timber props. Weights were used as temporary anchoring.

Fig 6.38 Material Connections workshop, 2013 The canvas was hydrated and left to cure to form a 10mm stiff surface shell.

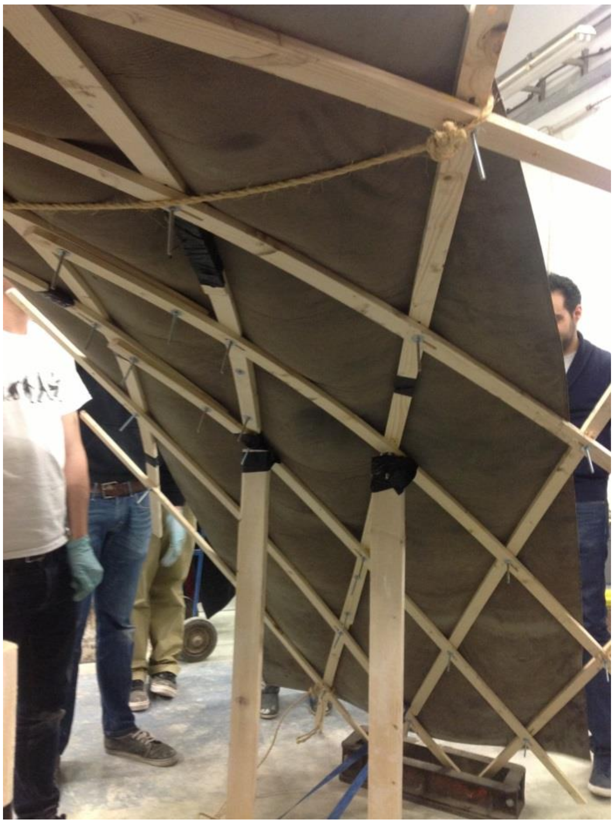


Fig 6.39 Temporary timber props/ support key points of the gridshell.

Fig 6.40 Concrete canvas when hydrated becomes heavy to drape between grid laths resulting in cushioning effects

Fig 6.41 Due to the even thickess of the 10mm concrete canvas,cushioning effects are expressed on the upperside of the shell as well.

Fig 6.42 “The Veiled Christ” by Giuseppe Sanmartino 1753

Discussion

The test re-used timber sections from the 2011 workshop.

In terms of construction, concrete canvas allowed a consistent shell thickness to be achieved. Hosing down concrete canvas to hydrate and activate cement embedded within the fabric can be a messy process. Questions of scale and how the material is stitched to join and expand are raised as a result of the test.

In aesthetic terms, the concrete canvas expressed the formwork clearly on the under and upper surfaces. The expression of the gridshell formwork is reminiscent of stone sculptures popularly produced in the 18th century which featured religious figures enshroud in veils and fabric. The 1753 work - The Veiled Christ by Giuseppe Sanmartino bears strong resemblance to this idea (fig. 6.42). The fluid and transparent aesthetic effect of a skilled stonemason was replicated two centuries later using a completely different technique.

6.7 Novelty of Hypothesis:

Having presented the hypothesis at various international conferences, there is a shared agreement by the scientific community that this technology has not been used previously. There are however close examples of gridded timber frames upon which concrete was applied:

6.7.1. Office and House 1988 in Hirituka City, Kanagawa, Japan by Shinji Yoshino, Tokyo engineered by TIS & Partner

A mixed use project by Shinji Yoshino (Herzog, Natterer, Schweitzer, Volz and Winter, 2004 p 252), the roof is an example of a 500mm spacing timber gridshell supporting a concrete shell above. With M10 bolts securing them together at their intersection, it was first assembled flat on the ground using 70mm x 35mm glulam sections. Timber spacers 70 x 35mm are used between the overlapping laths. Reinforced concrete was then applied over this gridshell. Excess ribs were cut back to fit the edges of the shell supported. The shell was trimmed by a timber glulam edge beam formed from two pieces of glulam timbers measuring 15 x 170mm.

110 · Office and house

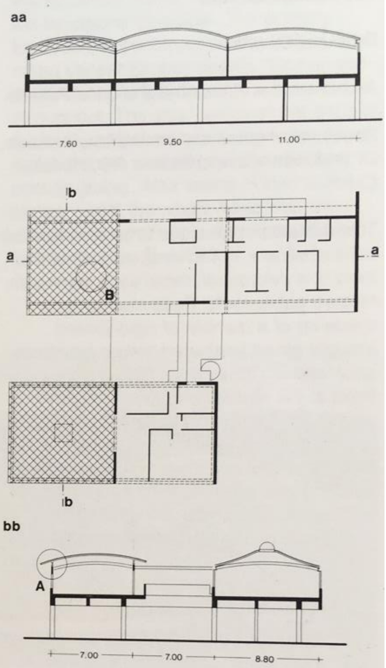
Hirituka City, Kanagawa, J; 1988

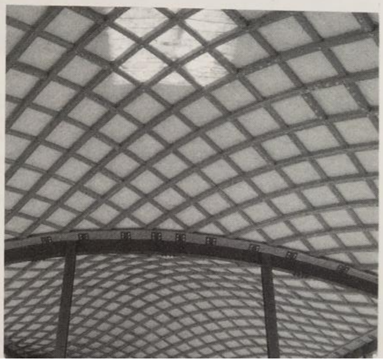
Architect: Shinji Yoshino, Tokyo, J

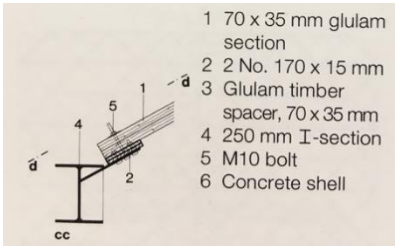
Structural engineers: TIS & Partner

During construction the timber lattice shell – in double curvature and without intermediate columns – supported the formwork for casting the five concrete shells that form the curving roof. In the finished condition it remains as an exposed element without any loadbearing function. The timber ribs were assembled on the ground in a 500 mm square mesh. This comprises two layers of boards bolted together at the intersections, plus timber spacers. After lifting into position they were joined to the timber edge members in their final position. The excess rib lengths were cut back to suit at the edges. The shell was cast after attaching the permanent formwork and fixing the reinforcement.

Space Design 1/89







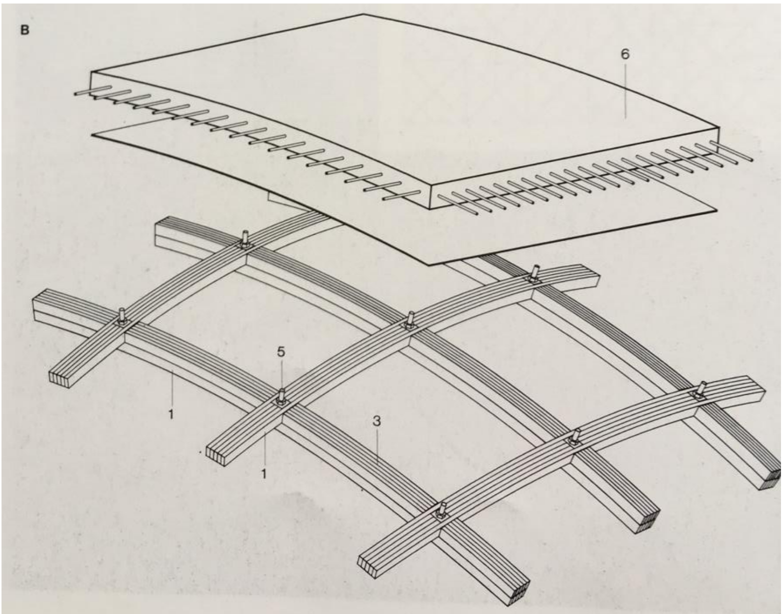


Fig 6.43 Office and House 1988 in Hirituka City, Kanagawa, Japan by Shinji Yoshino, Tokyo engineered by TIS & Partner (Herzog, Natterer, Schweitzer, Volz and Winter, 2004 p 252)

6.7.2. Naiju Community Centre and Nursery school, Fukuoka, Japan 1994 and Uchino Community Centre in Fukuoka, 1995 by Shoei Yoh.

The Japanese architect Shoei Yoh designed concrete structures using a similar method to the hypothesis in the 1990s. These concrete structures were constructed by applying concrete onto steel meshes laid onto a bamboo gridded sub-frame. Bamboo was first sliced into thin lath members and woven by hand in the spirit of Japanese craft tradition by the local community.

For the Naiju Community Centre (1994), the central area was crane lifted and once the shape was reached, a membrane was fixed onto the sub-frame and concrete applied. The bamboo was left exposed to the interior of the building, to display the woven bamboo basketry. This technique was used again a year later at the Uchino Community Centre. Excitingly, this was an early example of computational form-finding which worked out how the mat was bent into shape. Temporary scaffolding was used to support the bamboo gridmat whilst concrete was applied and the single space was illuminated from a central skylight.

Fig 6.44 shows the internal space of the Naiju Community Centre by Shoei Yoh Architects. The bamboo grid mat that supported the concrete left in-situ was crafted by the local residents.

Fig 6.45 The concrete roof of the Uchino Community Centre was constructed in a similar method (courtesy of Architect Shoei Yoh)

Fig 6.46 The concrete roof of the Uchino Community Centre 1995 was constructed in a similar method. (courtesy of Architect Shoei Yoh)

6.7.3 Other Related contemporary research

- Work of Olivier Bavarel in the Solaris pavilion in Paris, 2011 used composite GFRP tubes to create a temporary pavilion. The pavilion which measured 300 m2, was covered with a PVC membrane (Baverel et al, 2012).
- The Ephemeral Cathedral of Créteil at Paris, France, is a gridshell structure made of composite materials. Built in 2013, the 350 m2 religious edifice is a temporary church where parishioners gathered during the two year renovation of their permanent cathedral. (Du Peloux et al, 2011).
- CODA in Barcelona, a young company that deals with the design and construction of lightweight structures, addressed the concerns of the resource conscious climate. They built many interesting but small scale structures in Spain and increasingly worldwide. In 2012, they completed a timber gridshell in Barcelona called *Jukbuin* which was inspired by the tri-axial weaving of timber strips (Chilton and Tang, 2017).

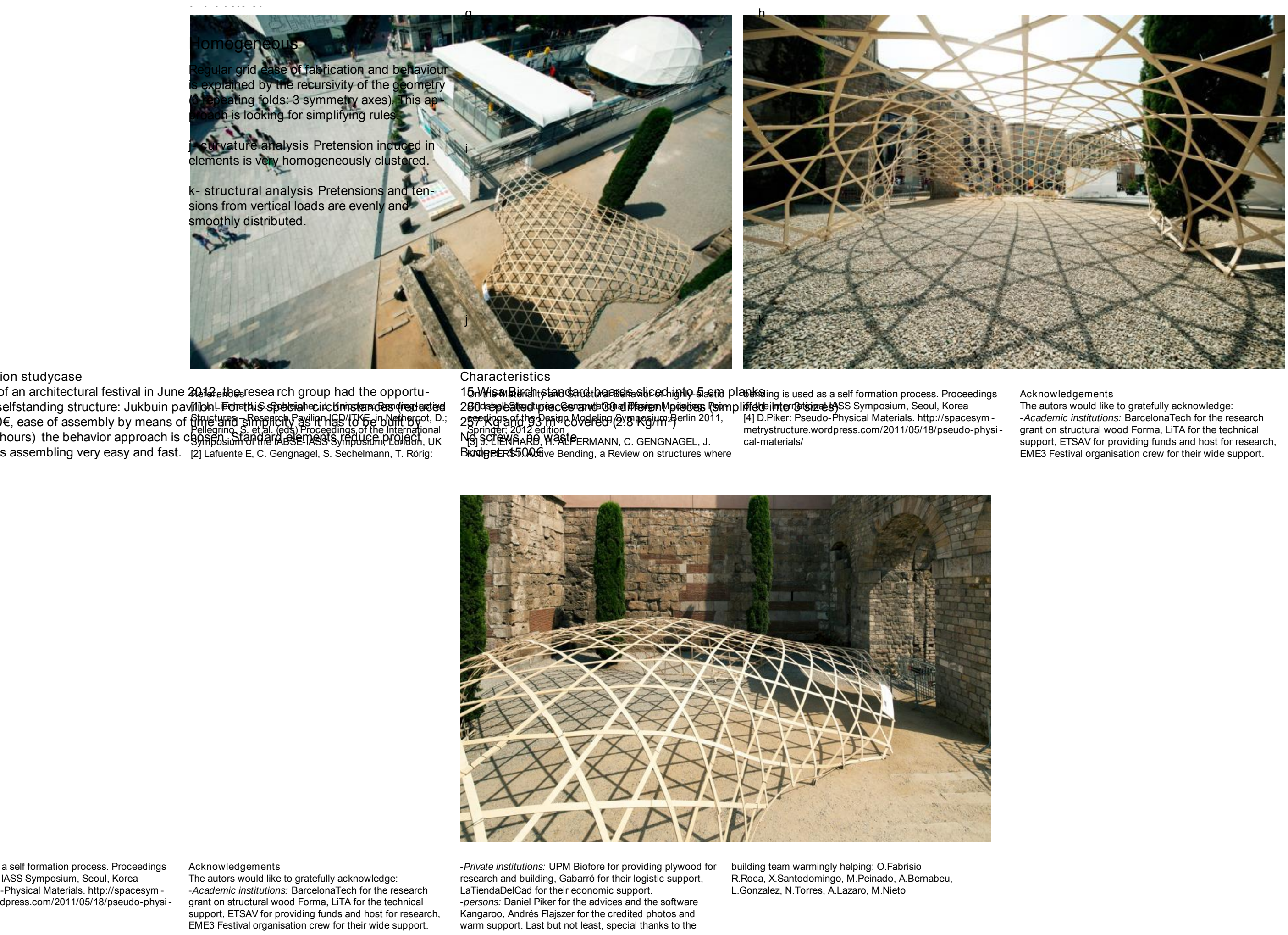


Fig 6.47 The Jukbuin Timber gridshell built in Barcelona (credit: CODA Barcelona).

- Actively-bent structures is also a research interest of Christoph Genganel (Universitat der Kunst, Berlin) which saw the inquiry of using pneumatics as a means of erecting a deployable and actively bent gridshell (Quinn and Gengnagel, 2014).

6.8 Research Questions

To investigate this, specific issues need to be addressed. The following sections examine the feasibility through a series of experiments to verify and analyse this hypothesis.

6.8.1 Questions on Formwork:

- Can a deployable gridshell be used as formwork for casting concrete shells?
- Is this formwork re-usable?
- Is this formwork deployable and how deployable is the formwork?
- What is the behaviour of the gridshell before, during and after casting?
- How easy is it to remove the gridshell after the concrete is cured and hardened?

6.8.2 Questions of Shell Casting Process:

- Observations during the casting process: what was the ease of applying concrete on the system and how does this affect the shape of the resultant concrete shell?
- What is the behaviour of the deployable gridshell before, during and after the casting process?

6.8.3 Questions on the resultant concrete shell:

- The geometry and shape of the resultant concrete shell
- How strong and stiff is this concrete shell?
- What is the expected failure mode of the concrete shell?
- What is the actual failure mode of the shell?

The question about this construction method will be investigated through a series of construction tests. Inferences, evaluation and deduction are made from of each experimental build.

6.8.4 Gridshell Material

To prevent weather conditions from affecting the structural integrity of the gridshell, as experienced by the failure of the shell constructed outdoors in 2011, waterproof plastics glass reinforced plastics and metal gridshells were tested instead. Materials whose mechanical properties unaffected by moisture will be specified for explored as contact with wet concrete may degrade the load-bearing capacity of the gridshell. Very importantly, materials need to be selected for cost and workability.

6.8.5 Concrete Mix

The concrete mix will determine the strength of the resultant concrete shell. As a constant, concrete mix of sand and cement with the addition of plastic fibre reinforcements is used. To adjust viscosity, the amount of water will be varied as this will have an influence on the application process. The constitution of the concrete mix is recorded and described in each tests in chapter 7.2.4, 8.3.5 and 9.3.2.

6.8.6 Reinforcements in concrete

Traditionally, pre-tensioning cables and steel mesh reinforcements are incorporated into concrete shells (those by Candela) and thin shell structures (masonry shells by Dieste) to overcome bending and tensile stresses. For this set of concrete shell constructions, reinforcement bars are excluded as the aim of this experiment is to understand the true structural behaviour of the concrete shell which are constructed of simple geometries without extreme curvatures.

6.9 Prototype and Testing

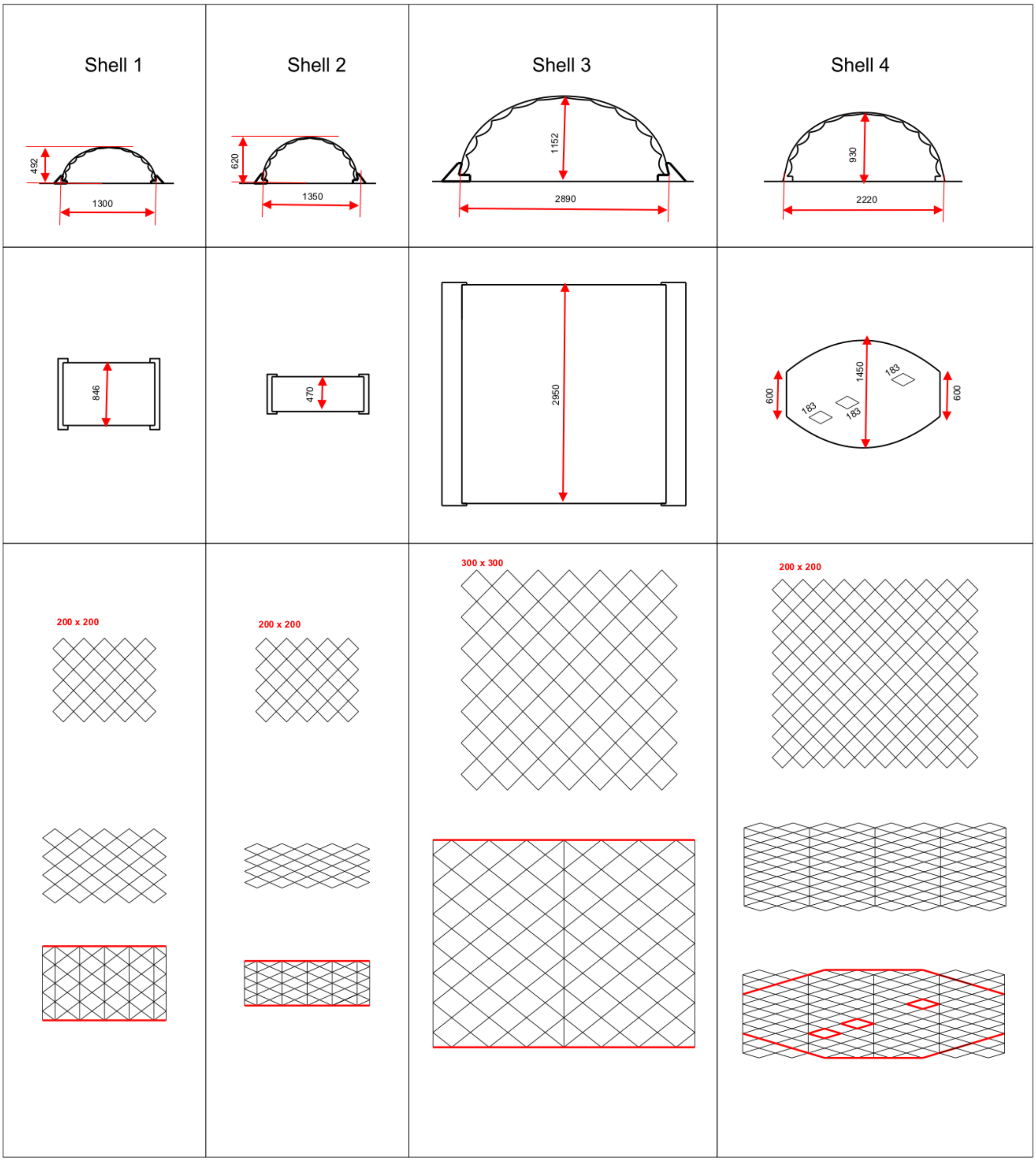


Fig. 6.48 Chart of Experimental builds using deployable and actively-bent gridshells as formwork for concrete shell casting.

In view of all questions raised with regards to this construction technology, a series of four construction experiments are set up to interrogate these ideas. The shells underwent a series of deflection, failure testing and finite element analysis in collaboration with engineers and engineering students. The main aims of these construction tests are outlined below.

6.9.1 Test Shell 1 and Test Shell 2 (Chapter 7):

Aims:

- To understand formwork behaviour and concrete shell behaviour of a single curvature
- To verify reusability and configurability of gridshell formwork
- To understand behaviour of gridshell formwork i.e. formwork movement when concrete is applied.
- To understand structural behaviour, within elastic range and loading capacity of the shell
- To explore tectonic and structural implications of undulating concrete cushioning

6.9.2 Test Shell 3 (Chapter 8)

Aims:

- To understand formwork behaviour and concrete shell behaviour of a double curvature
- To verify the suitability of metal sheets in creating a gridshell formwork.
- To experiment with curvature adjustments in a gridshell formwork to induce strong double curvatures.
- To understand the tectonic expression of this technology

6.9.3 Test Shell 4 (Chapter 9): Change in geometry, Openings and Free-edges

Aims:

- To understand formwork behaviour and concrete shell behaviour of a complex double curvature
- To experiment with free edges
- To simplify abutment detail
- To explore opening possibilities
- To explore the structural strength of a thin concrete shell
- To understand effects of concrete application on the final shell shape to explore the relationship between application and performance.

The final construction was built to express double-curvature, openings and free edges to demonstrate what these gridshells could produce.

6.9.4 Scaled Simulation of a concrete shell made using Weald and Downland gridshell in GFRP as formwork.

Aims:

- To understand construction of a concrete shell using a deployable gridshell as formwork to replicate the construction stages
- Finding out how much concrete the gridshell can support.

6.10 Conclusion: Limitations. Discussion and Summary

The limitations of the hypothesis are informed by characteristics and limitations of all three technologies (concrete shells, fabric formwork and deployable gridshells). The following points are pertinent to the research:

- Being flexible and highly deflective/ reactive when concrete is applied, how then does the gridshell achieve an accuracy?
- The size of a manageable gridmat may limit application in particular situations such as at an urban build-up area as it requires extensive open space for handling/ manipulation.
- Grid size affects gridmat flexibility. This factor influences the use of fabric as a surface upon which concrete is applied. This also affects the structural depth of resultant concrete shell to induce additional stability.
- The management and control of the shell thickness is also an important point to consider as
- Abutments would influence the way gridshells meets the ground to form effective anchorages.
- Windows and glazing treatment are design aspects to consider. Curtain walling may be used to demonstrate structural capability of the shell. For example, at the Los Mantiales, Xochimilco (1958) restaurant, the glazing line recedes inwards from the roof (i.e. shell) to express that the shell is self-supporting and was not borne on the glazing bars as was at case at Kresge Auditorium at MIT (Chapter 3.2.1.3).
- Specialist form-finding softwares, which are difficult to use, may deter architects and engineers from using this technology. As such, other methods of understanding this may be required. This may take the form of physical models of deployable gridshells and hanging nets to understand spatial implications of the designs.
- Decentring sequencing require careful consideration. Whether or not formwork was removed in sections or in a single piece requires careful planning whilst concrete is cured and develops structural strength.
- Whether or not gridshells are assembled on site or prefabricated off-site are practical points for consideration.
- Openings in the proposed system allowing light penetration may be an issue as it may compromise the structural continuity of the shell.
- The beauty of the gridshell rests on the fact that it describes the geodesic lines and forces are concentrated in the gridlines. As such, openings are possibly located within the grid spaces which may order the rules of designing using this system.

The following chapter begins PART III of the thesis: construction and testing in a series of tests outline earlier.

Interior, Cadyl Grain Silo at Young by Eladio Dieste, Uruguay (1979), 2017 (Gabriel Tang)

PART 3 CONSTRUCTION AND TESTING

Chapter 7 VERIFICATION OF HYPOTHESIS

Chapter 7 Verification of Hypothesis

7.1 Aims of Test

- To evidence re-deployability of grid shell by building two concrete shells of single curvatures from one single set of gridshell formwork with fabric covering at relatively small scale
- To study construction process, deformation/ deflection of form during casting
- To verify reusability and reconfigurability of gridshell formwork
- To understand behaviour of gridshell formwork i.e. formwork movement when concrete is applied.
- To understand structural behaviour, within elastic range and loading capacity of the shell
- To explore tectonic implication of undulating concrete cushioning

Experimentation and Building of Deployable Gridshells as formwork for concrete shells August 2014

Fig 7.1 Shells 1 and 2 constructed using the same deployed gridshell formwork

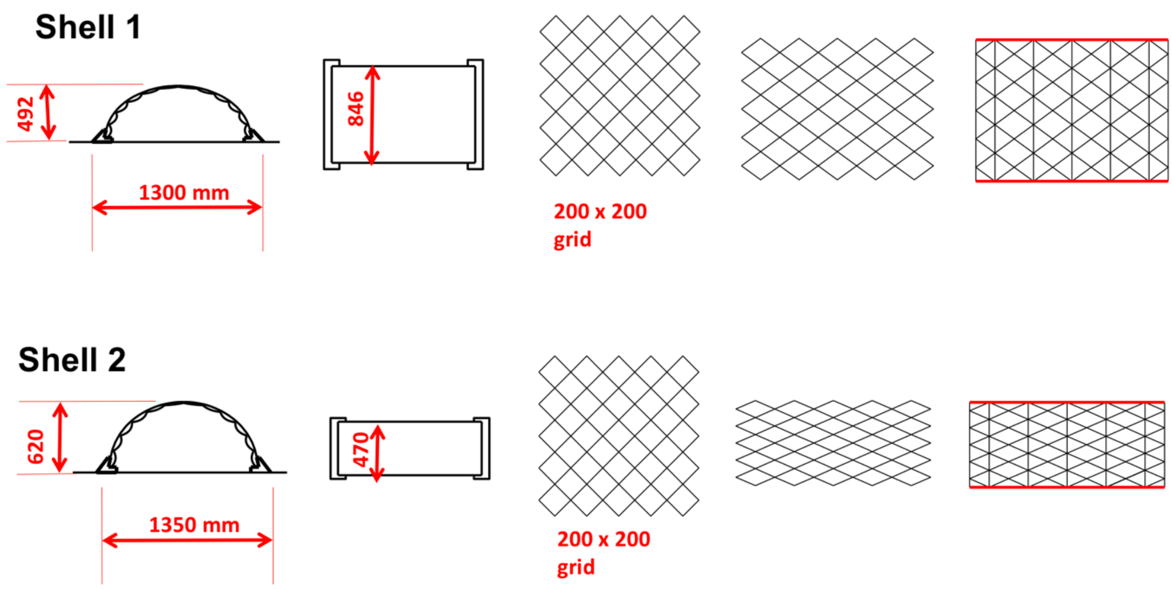


Fig 7.2 Shells 1 and 2 are constructed using the same deployed gridshell formwork

This section examines the effectiveness of using a deformable gridshell as a re-useable formwork system as follows:

- Construct 2 simple vaulted shells with geometries using the same gridshell to support a fabric layer.
- Following small scale model studies, a gridshell is made from PVC plastic conduit piping with an elliptical profile 16mm wide by 10mm deep was bolted together with plastic binding screws commonly used in book binding. These allowed the free-rotational scissor joints and allowed the flat mat to deform into a 3D shape.
- This flat plane is now bent and propped against 2 prefabricated abutments affixed to a pre-made timber platform base.
- Once the required form is obtained the geometry is locked in place by adding additional struts to triangulate the gridmat to temporarily restrain the gridshell formwork.
- A poly-propylene woven fabric was then stretched over the gridshell to support the concrete.
- Concrete was then applied directly to the fabric.
- Once the concrete has set, the gridmat was then removed from under the concrete shell.
- To create the next shell, the bracing that triangulates the structure and therefore fixes in their dimensions were removed from the gridmat. With the joints free again, the same gridmat was deformed into a flat mat with a different geometry to produce a shell that was longer and narrower than the first. The second taller shell was constructed on a different set of abutments.
- After this, the steps of casting and assembling and dissembling are again repeated to test the viability of this method of construction.

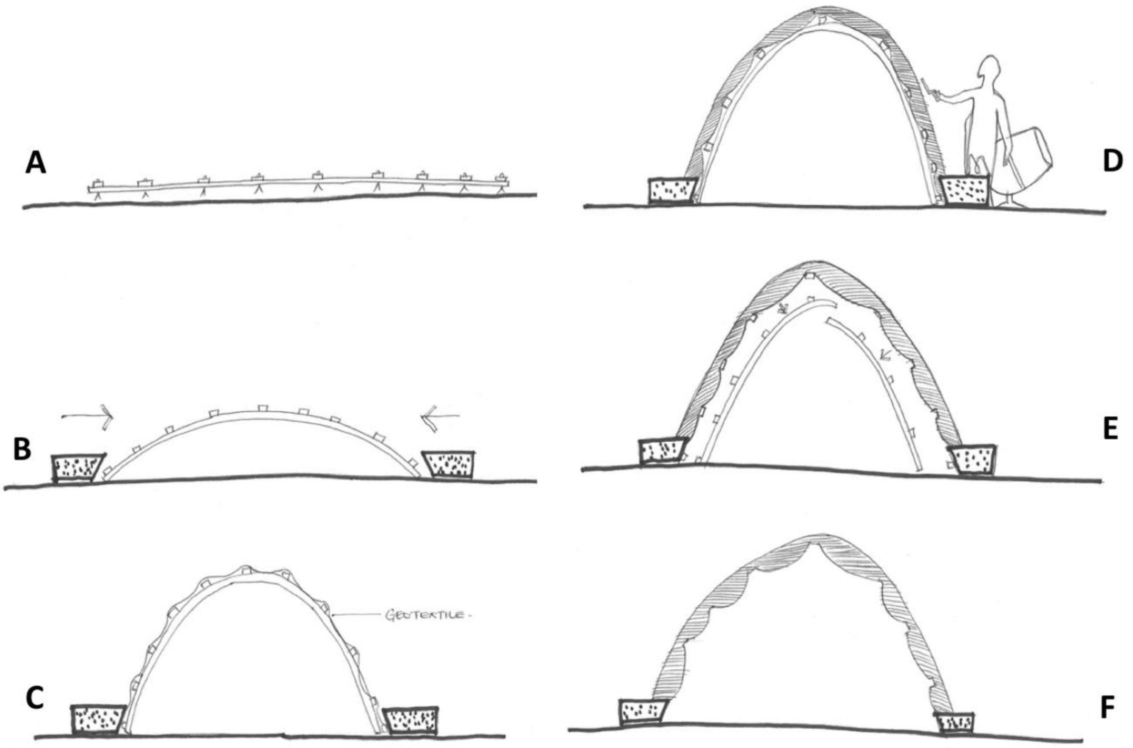


Fig 7.3: Stages of construction of gridshell use as formwork.

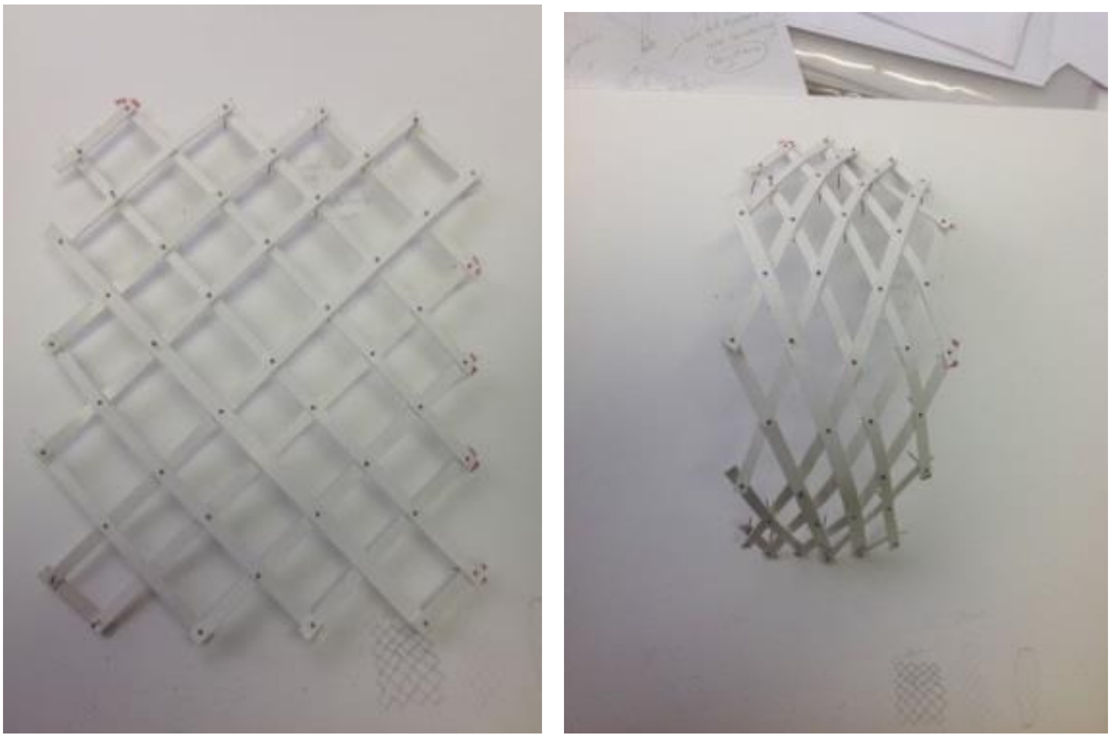


Fig 7.4 Gridshell model is opened up and then compressed into an arch

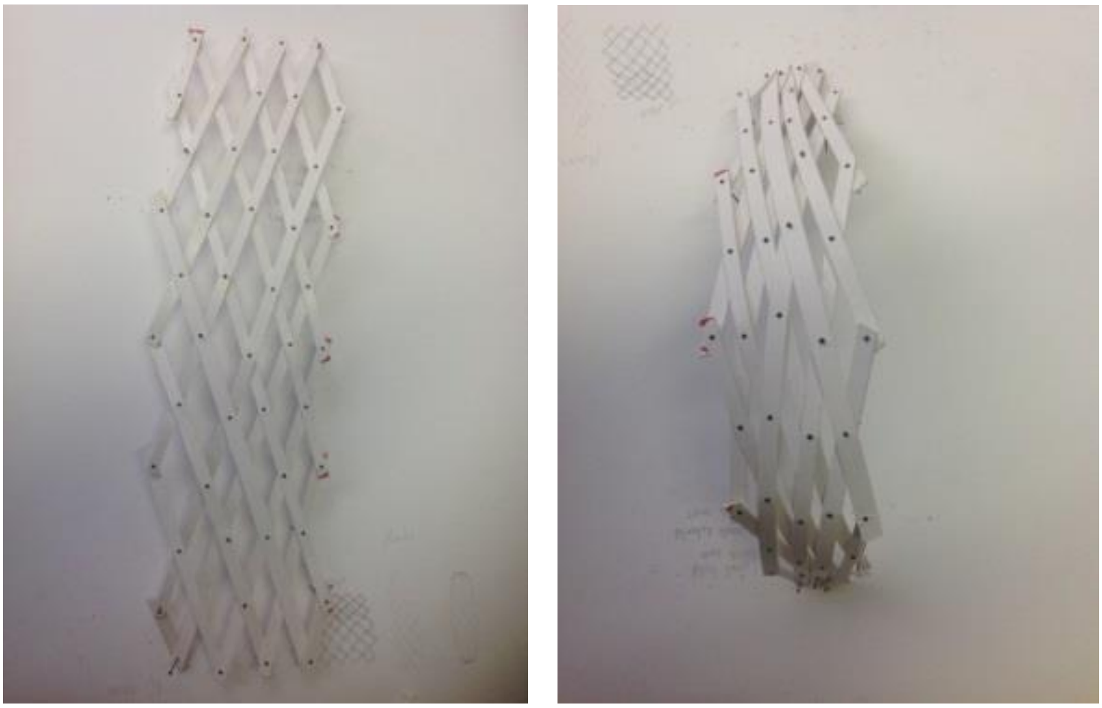


Fig 7.5 Gridshell model is deployed to form a longer mat and eventually creates an arch.

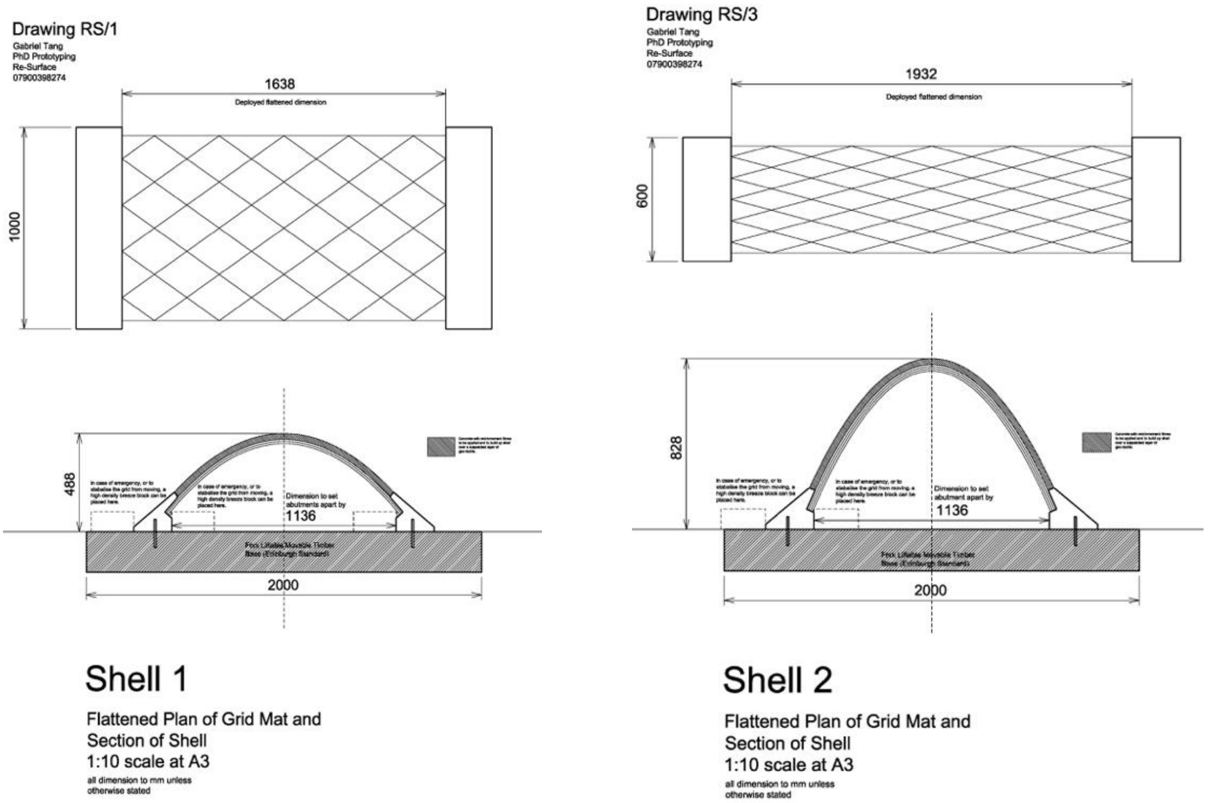


Fig. 7.6: Construction drawings.

7.2 Test

7.2.1 Materials used in the construction of the gridshell formwork:

The gridshell was constructed at the concrete research workshop at Edinburgh University. 3m lengths of poly-vinyl-chloride (pvc) pipe electrical conduits elliptical sections with section profiles 16mm wide, 10mm deep were used. They were drilled with 5mm diameter holes at 200mm centres to allow for binding screws to connect the top and bottom layers to form rotation joints. Plastic screws with a diameter of 5mm and of varying lengths of 20mm, 30mm and 40mm were used. The screws were also chosen due to their relatively flat head to reduce protrusion and which might catch and tear the fabric. Polypropylene woven textile was used for the fabric formwork manufactured from JD Wilkie.

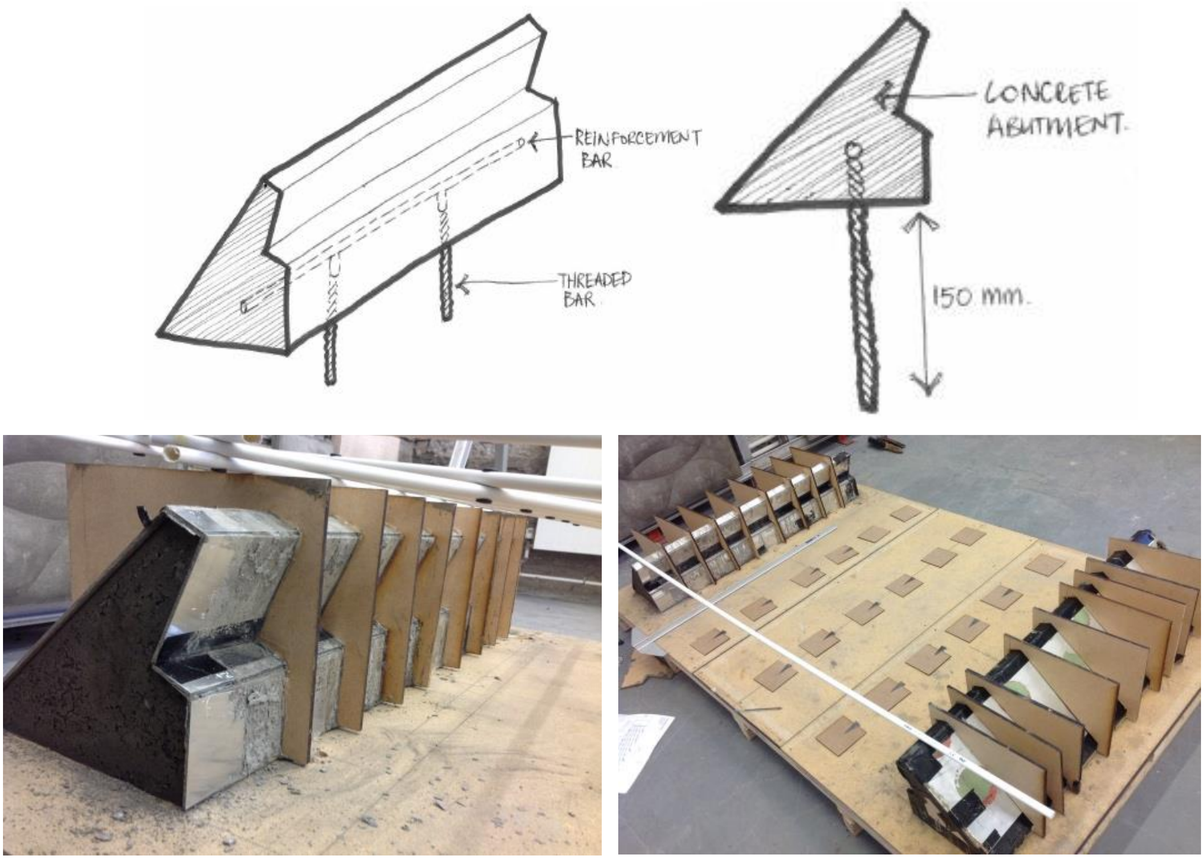


Fig. 7.7: Detail sketch (top), abutment construction (below)

7.2.2 Abutment Design:

The abutments define the structural behaviour of the shell, providing both vertical and horizontal restraint. The abutments were cast in two different sections using 5mm thick acrylic plastic sheets taped together. The formwork was supported along the length with nine 5mm mdf boards laser cut for each abutment. The abutments were reinforced as well (fig. 7.7 top left). Additionally, 2 threaded steel rods were cast into the concrete to connect the abutment to the baseboard platform designed to allow forklift access. The 4 abutments were cast using a 3 part 10 mm aggregate, 2 sharp sand, 1 part cement mix.

7.2.3 Designing and Building the Baseboard:

Given the space constraints in the workshop the shells were constructed on specially designed bases to allow for easy re-locating. Each shell sits within its own baseboard raised off the ground on a base with timber struts for access and manoeuvred with a pallet truck when necessary shown in Figure 7.7. This elevation also allows the abutments to be screw bolted and attached to the baseboard.

7.2.4 Concrete Mix for the shell:

The concrete mix for the shells is intentionally dryer than the usual consistency to prevent slippage and concrete sliding off the fabric formwork. No steel reinforcements were used in the shell, but 20 mm Strux polypropylene fibres were added in the mix. The concrete mix consisted of:

62.5kg sand,
25kg cement,
150g 40mm Strux 90/40 Synthetic Macro Fibre plastic reinforcement
14 x 600ml water

7.2.5 Stages of Construction:

Abutments: The abutments were cast and attached to the platform bases a week prior to the construction of the shells.

7.2.6 Preparing the gridshell formwork Building the grid-shell:

A 1:10 scale drawing of the plan of the gridshell was used as a reference plan to work out the exact number of pvc conduit pipes lengths and lengths of plastic binding screws to construct the gridmat. The PVC conduits were drilled with 5mm diameter holes spaced 200mm apart. Using 20mm long PVC binding screws, the flat deployable grid-mat was assembled.

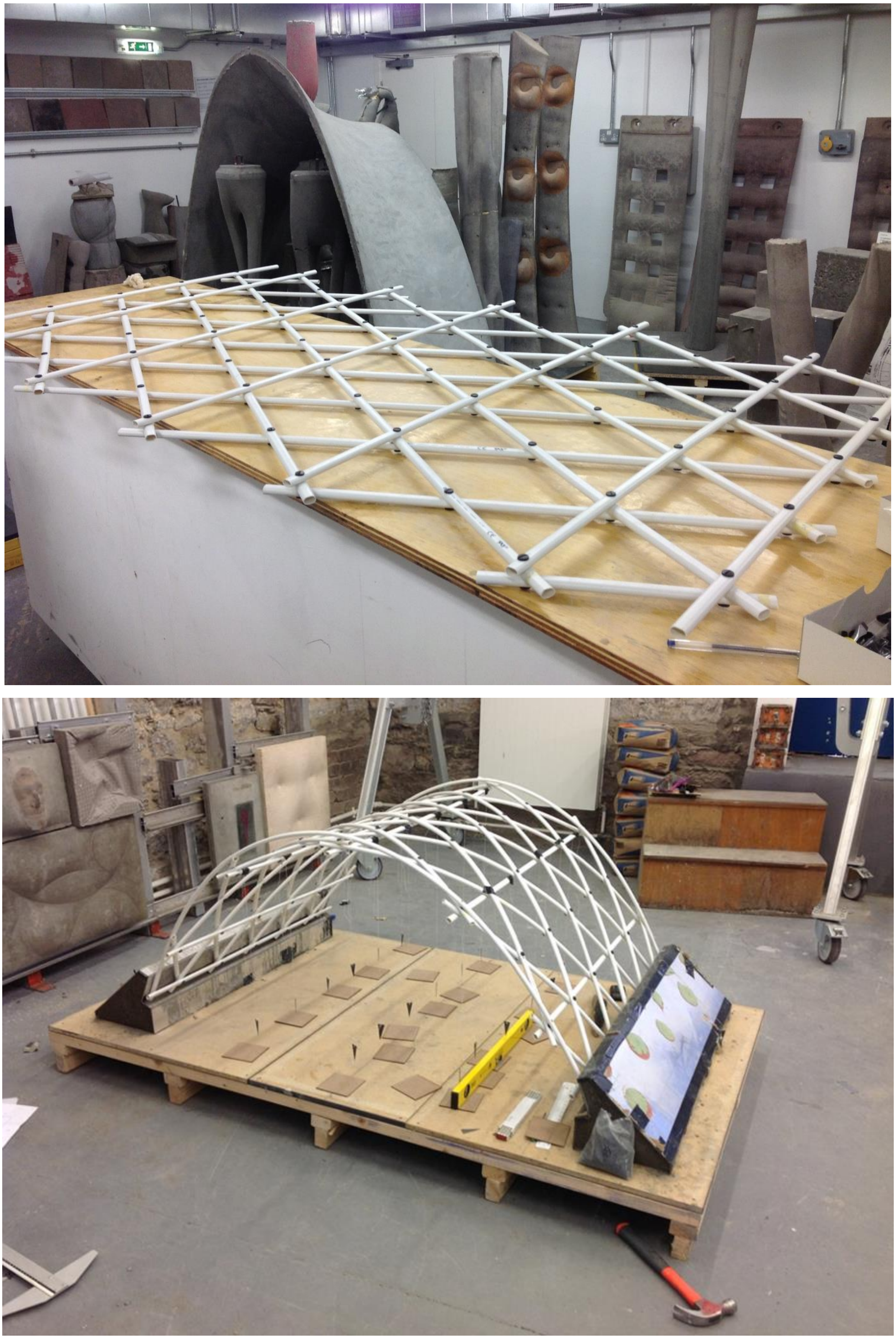


Fig. 7.8 PVC gridshell propped against pre-cast concrete abutments.

This gridmat was then extended to a flatten gridmat with an overall length of 1640mm, which determined the width of this gridshell. This elongated gridmat was then temporarily locked into position by securing cross members pieces in position at the points of intersection to triangulate and brace the structure. These are secured at each intersection using 30mm long binding screws through pre-drilled holes. This triangulated gridmat is propped between the concrete abutments to create an arched formwork.

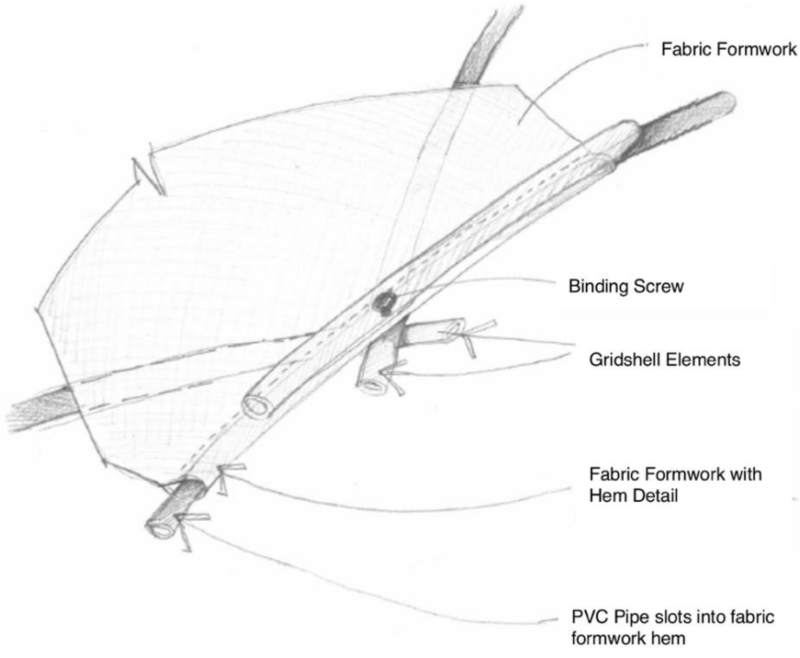


Fig 7.9: Fabric formwork and edge detailing

Fig 7.10 Forming the edge

To ensure a tight seal that did not produce gaps that allowed the concrete to escape, a hem/pipe detail was sewn into the fabric through which pvc conduit members were fed through (fig 7.10). An additional plastic pipe on each edge was attached on top of this structure with binding screws to produce a shallow tray detail. This edging piece not only held the concrete in place, it also defined and accentuated the shell edge thinness. With a depth of this measuring 10mm, the concrete shell clearly expressed this thinness when formwork system was removed. Material continuity was achieved where the shell met their abutments. With a supporting pvc structural gridshell and fabric formwork that was placed above to support the concrete and prevent it from falling through, the material arrangement and the sequence of formwork removal was important. To prevent the fabric formwork from being caught between the abutment and the resultant concrete shell, special care was taken to ensure surplus fabric was folded under the “tongue” of the abutment (fig. 7.11 and 7.12).

Fig 7.11 Temporary timber props to prevent concrete from flowing out of formwork at abutment.

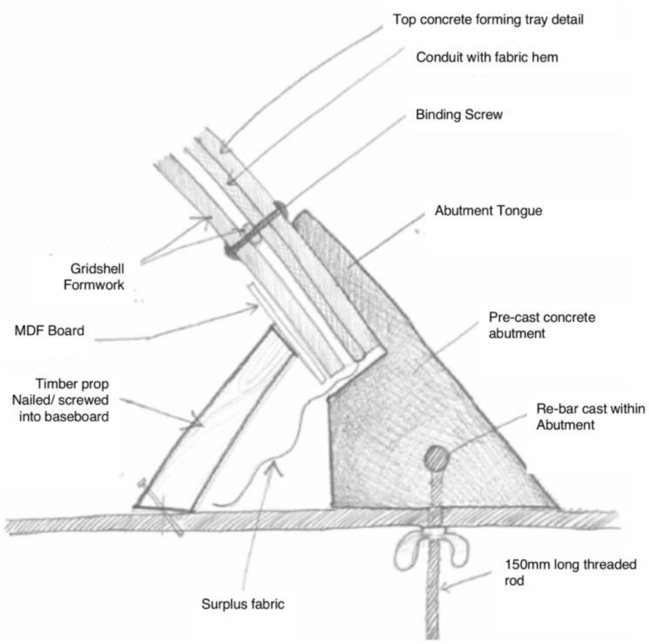


Fig 7.12 Abutment details

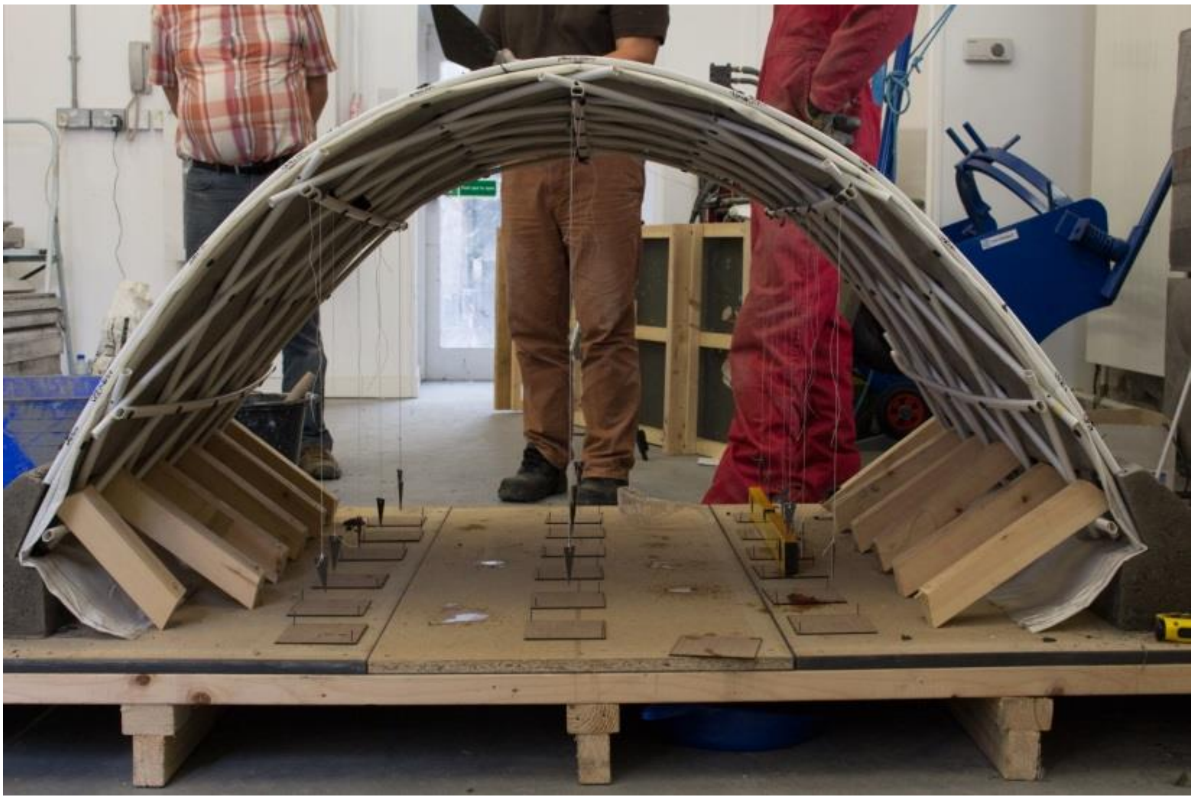


Fig 7.13 The completed gridshell formwork

Fig 7.14 Temporary timber props push against an acrylic plate that prevented concrete from escaping.

To prevent concrete from slipping and leaking into the space below the abutment, an acrylic plate was installed on each side of the vault abutment and then temporarily propped against the abutment tongue using timber props screw onto the surface of the baseboard as shown in fig. 7.14.

7.2.6 Shell 1

7.2.6.1 Casting

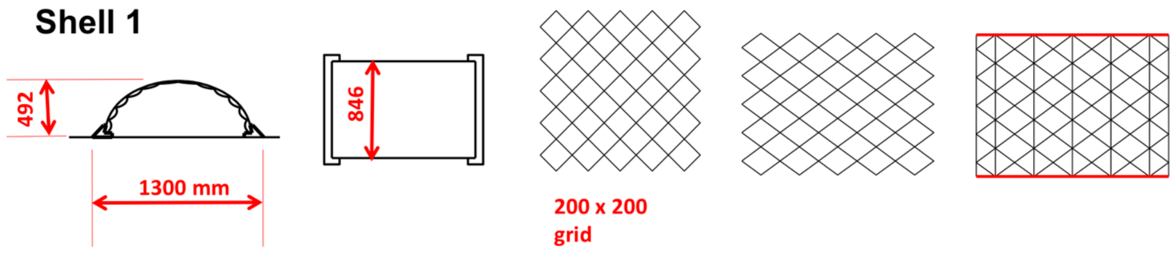


Fig 7.15 Concrete was applied at the bases near the abutment first, then the top and then at quarter spans. Both fabric and gridshell are highly flexible.

Once the formwork was ready, concrete was applied. A scratch coat (approximately 10mm thick) of concrete was first manually trowelled onto the polyester fabric starting from both abutments. Concrete was then applied at the apex. The concrete was gradually worked from the apex and moved towards the quarter spans where they met.

When the initial scratch layer was complete, a pattern of scores was made. After a couple of hours as the concrete sets, another coat of concrete was applied following the same procedure. The 2 edge beams at the sides of the shell held the fabric together and acted as an effective beading to produce an edge that expressed the tectonic of gridshell and formwork.

Concrete filled in the diamond shaped spaces between the gridshell formwork to create an undulating cushion-like surface on the underside. The upperside had a smooth finish.

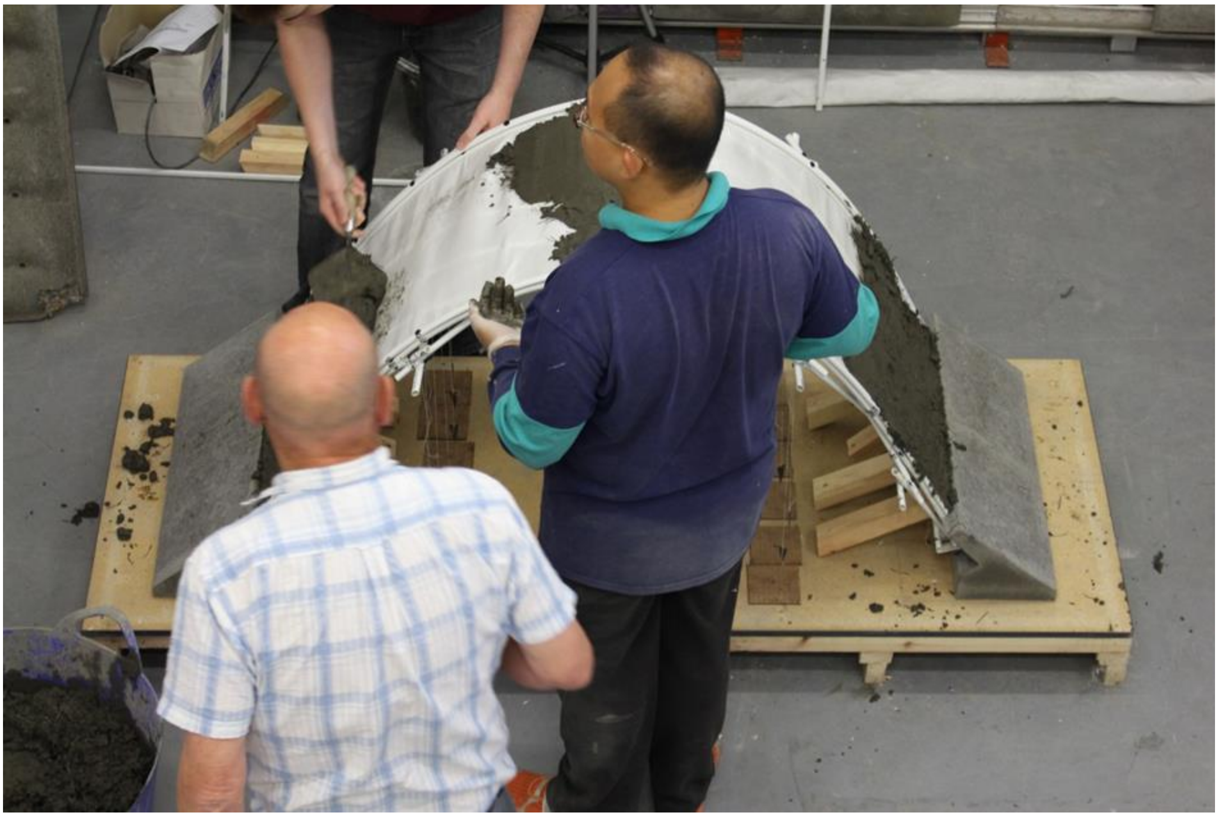


Fig 7.16 The concrete shell partially cast showing casting sequence.

During casting, deformations measurements were taken using a series of plumb lines projected onto a rectangular grid to understand how the gridshell moved as concrete was applied onto the gridshell (This is explained in more detail in the subsequent section, chapter 7.3.1).

As loading of concrete took place, the positions of plumb lines were marked and recorded indicating the movement of these points, describing the deflection along and offering an understanding of movement. After the scratch coat was applied, the movement of plumb line was measured again.

Fig. 7.17: Stages of construction

It was noted that the apex of the arch rose from 665mm when unloaded to 675mm during casting. The concrete shell was then left for 2 days to set and cure.

7.2.6.2 De-centring

After 2 days, the formwork was removed, the side rail pvc pipes were removed first. Then timber props were removed followed by timber bracing pieces were removed. Next, the fabric was removed in a process that took 15 minutes from start to finish.

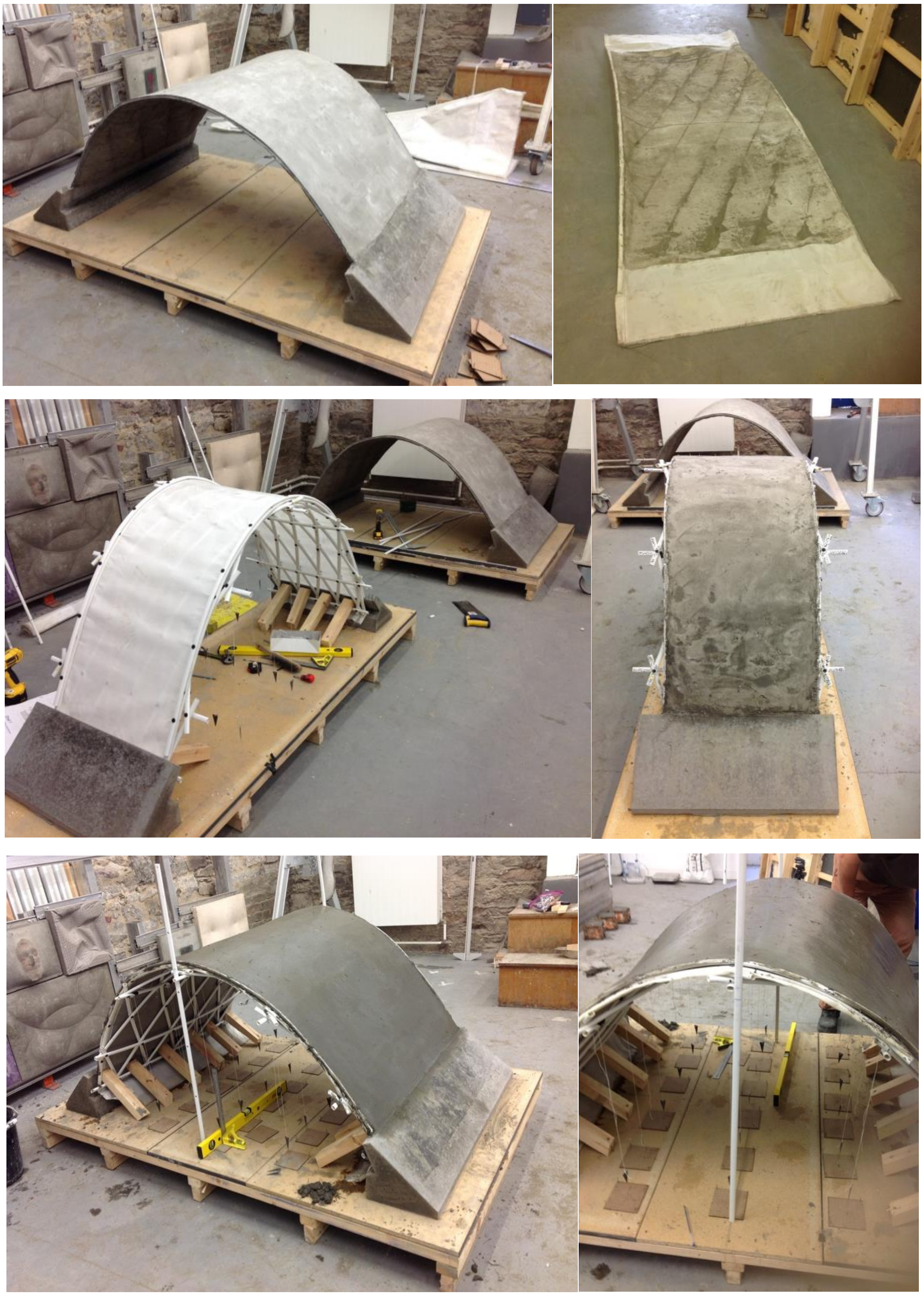


Fig 7.18 A photographic summary of test shell 1 and 2 construction.

7.2.7 Shell 2

7.2.7.1 Casting and Decentering

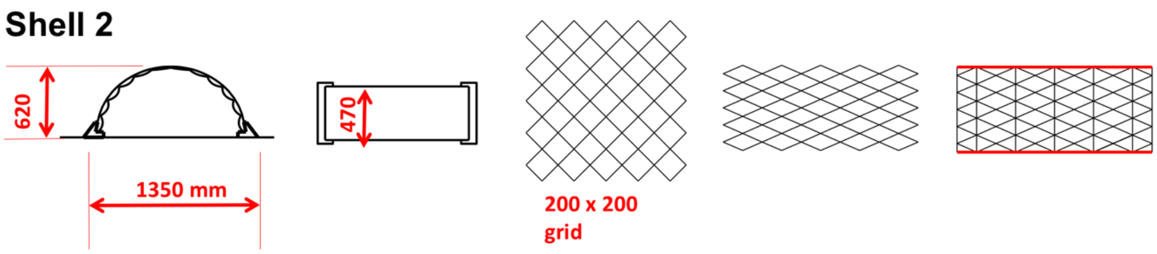


Fig 7.19 The overall comparison between both Shells 1 and 2

Casting shell two

After de-centering from shell 1, the gridshell was re-assembled onto the second base board and abutments to cast Shell two, this shell was longer and narrower than shell 1 with a width of 470 mm as opposed to 846mm of Shell 1. The shell was then cast following the same process as shell one. To assemble the formwork, cast, cure, strip, reassemble and re-cast was carried out over a period of five days.

Fig 7.20 Gridshell formwork was removed from the concrete shell in just 15 minutes.

Fig 7.21: Resulting concrete shell with a fine edge with a thickness of 11mm notice the indentation was the result of laying the 10mm pvc conduit to define this edge.

7.2.8 Workshop Construction: timetable

Description: Time scale and schedule of Construction

Wednesday	Thursday	Friday	Saturday	Sunday	Monday	Tuesday	Wednesday
Assembling materials to make the plastic gridshell	Fabric stretching and preparation of recording	Casting of concrete Completion	Curing	Curing	Stripping and removal of formwork. Preparing of recording instruments	Casting of concrete	Curing

Fig 7.22 Schedule of construction

The construction took a week i.e. 7 days including a 2 day weekend of curing time. Two test shells were constructed during this week.

Fig 7.23: Stages of construction: a) Abutments are affixed onto base board. b) gridmat is subtended between the gridmats. c) Fabric hemmed at 2 edges are secured onto gridmat tightly. d) Once fabric secured with an edging piece on both sides, mdf measuring boards are arranged to match plumb lines. e) concrete applied to both sides f)then top g) and h) concrete smoothened out and left to set before second layer is applied. i) Bracing sections are removed j) gridshell removed easily to be reused.

7.2.9 Discussion

The discussion is organised into three sections: namely:

1. Construction
2. Aesthetics and
3. Structural Analysis

7.3 Construction (Of Gridshell and Concrete Shell)

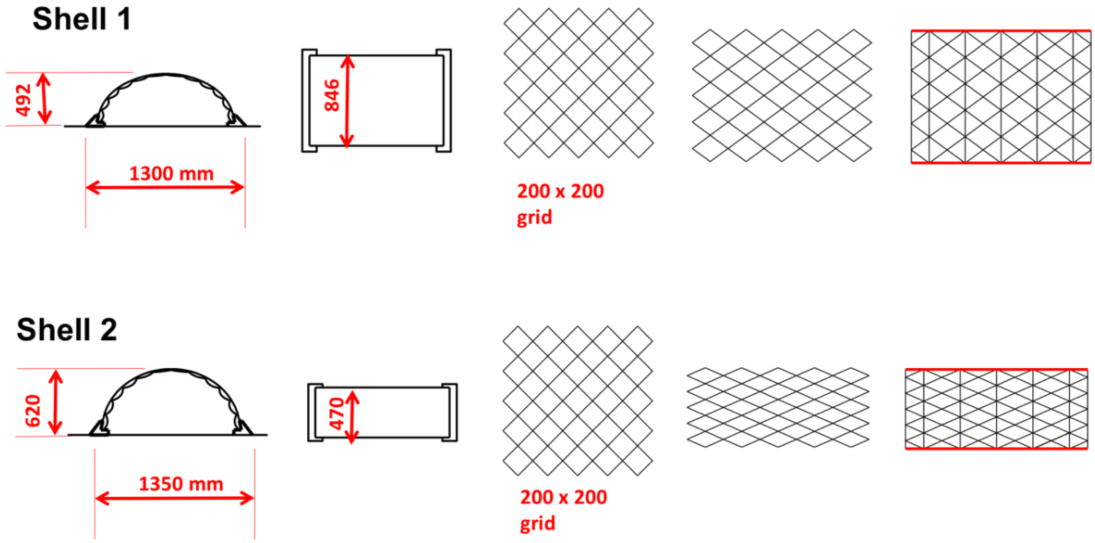


Fig 7.24 Test Shell dimensions

7.3.1 Process analysis: Understanding the behaviour of the grid shell during casting

To understand loading behaviour during the casting process, steel plumb lines were hung at 18 points from intersections at 50mm (the depth of a spirit level) above the measuring boards. This level was set as datum. 18 corresponding measuring boards A1 to C6 (fig 7.26) were made from MDF boards and laser cut. To locate each point location co-ordinate, they are assigned an x, y and z co-ordinate.

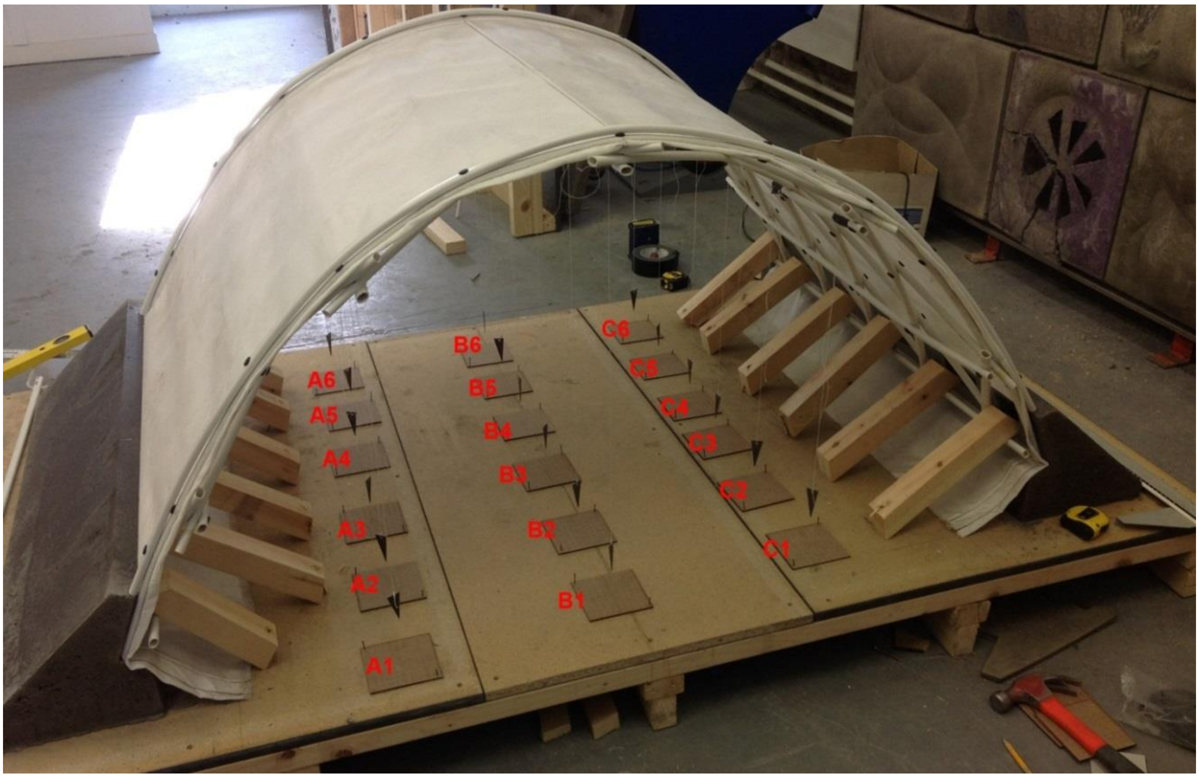


Figure 7.25: Left: location of plumb lines

Figure 7.26: recordings of displacements on measuring boards

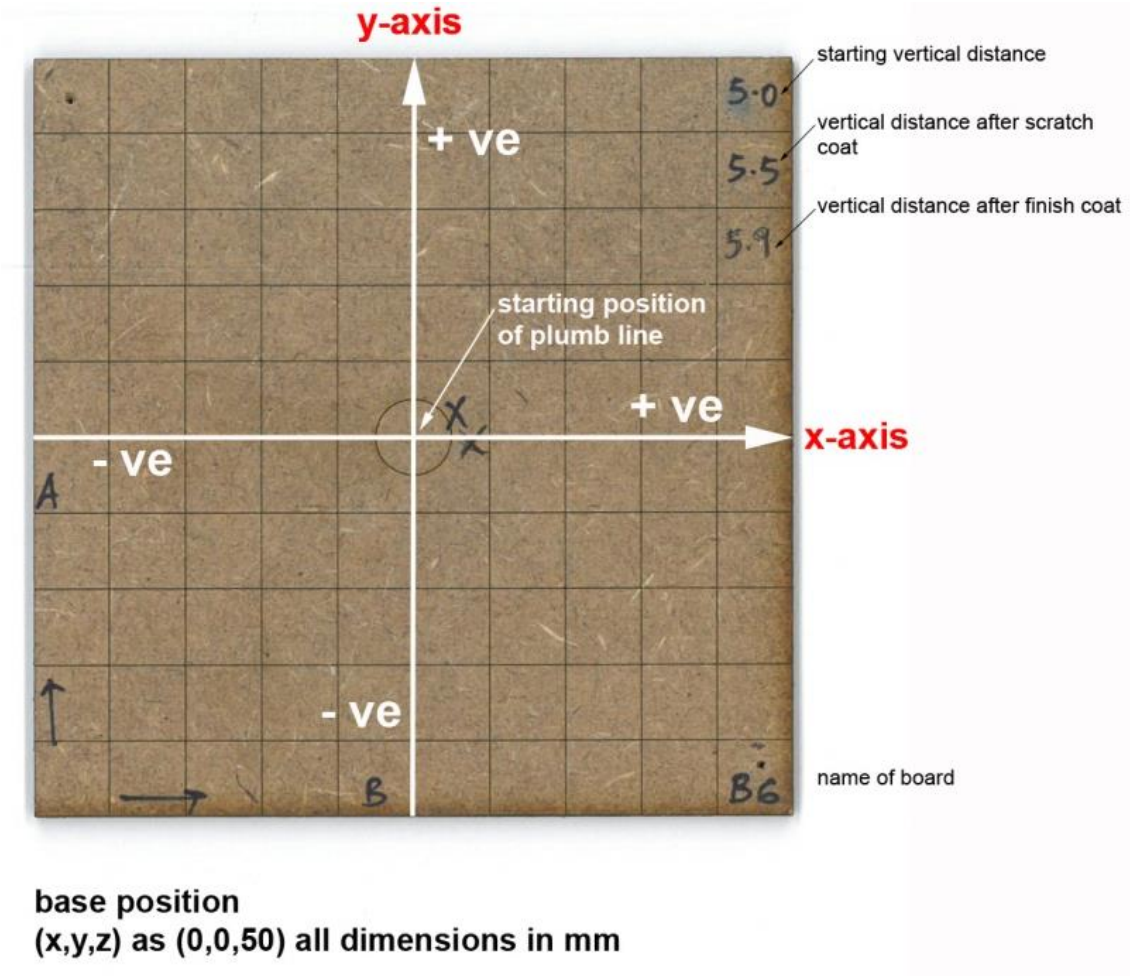


Fig. 7.27: recordings of displacements on measuring boards

This was the way to record deflection/ movement at specific points of the shell as it was loaded horizontally and vertically. These data are plotted on a 3 dimensional graph indicating each datum. The distance between each datum point is not to scale. Each small square represents 1mm on the x- and y-axis.

Movement of points during loading for Shell 1 after scratch coat

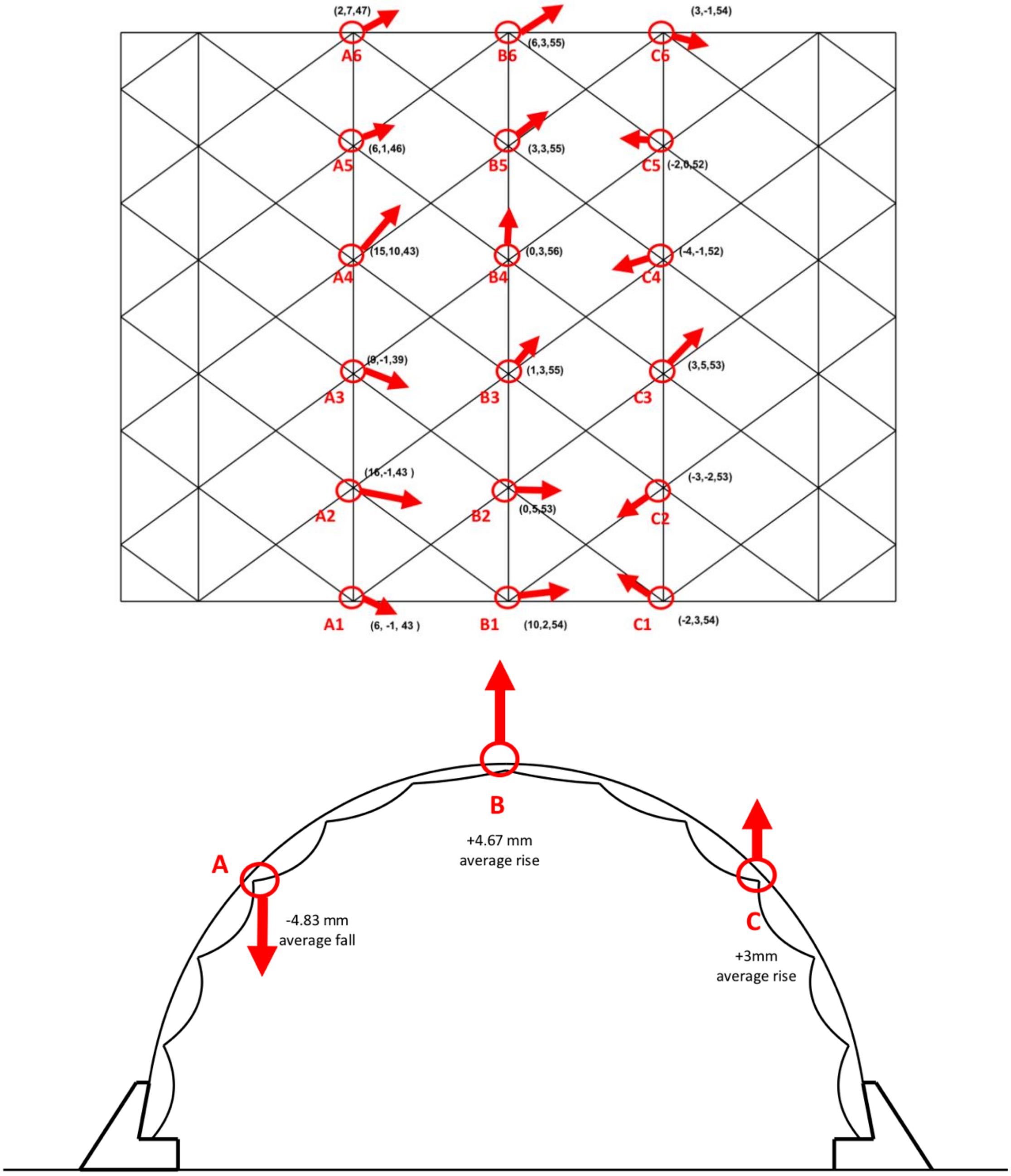


Fig. 7.28 Relative Movement of Shell 1 during casting scratch coat

Shell 1

When scratch coat is applied, the gridshell moved to the following positions

A6 (2,7,47)	B6 (6,3,55)	C6 (3,-1,54)
A5 (16,1,46)	B5 (3,3,55)	C5 (-2,0,52)
A4 (15,10,43)	B4 (0,3,56)	C4 (-4,-1,52)
A3 (9,-1,39)	B3 (1,3,55)	C3 (3,5,53)
A2 (16,-1,43)	B2 (0,5,53)	C2 (-3,-2,53)
A1 (6, -1, 43)	B1 (10,2,54)	C1 (-2,3,54)

Shell 1 Movement Diagrams after finishing Coat

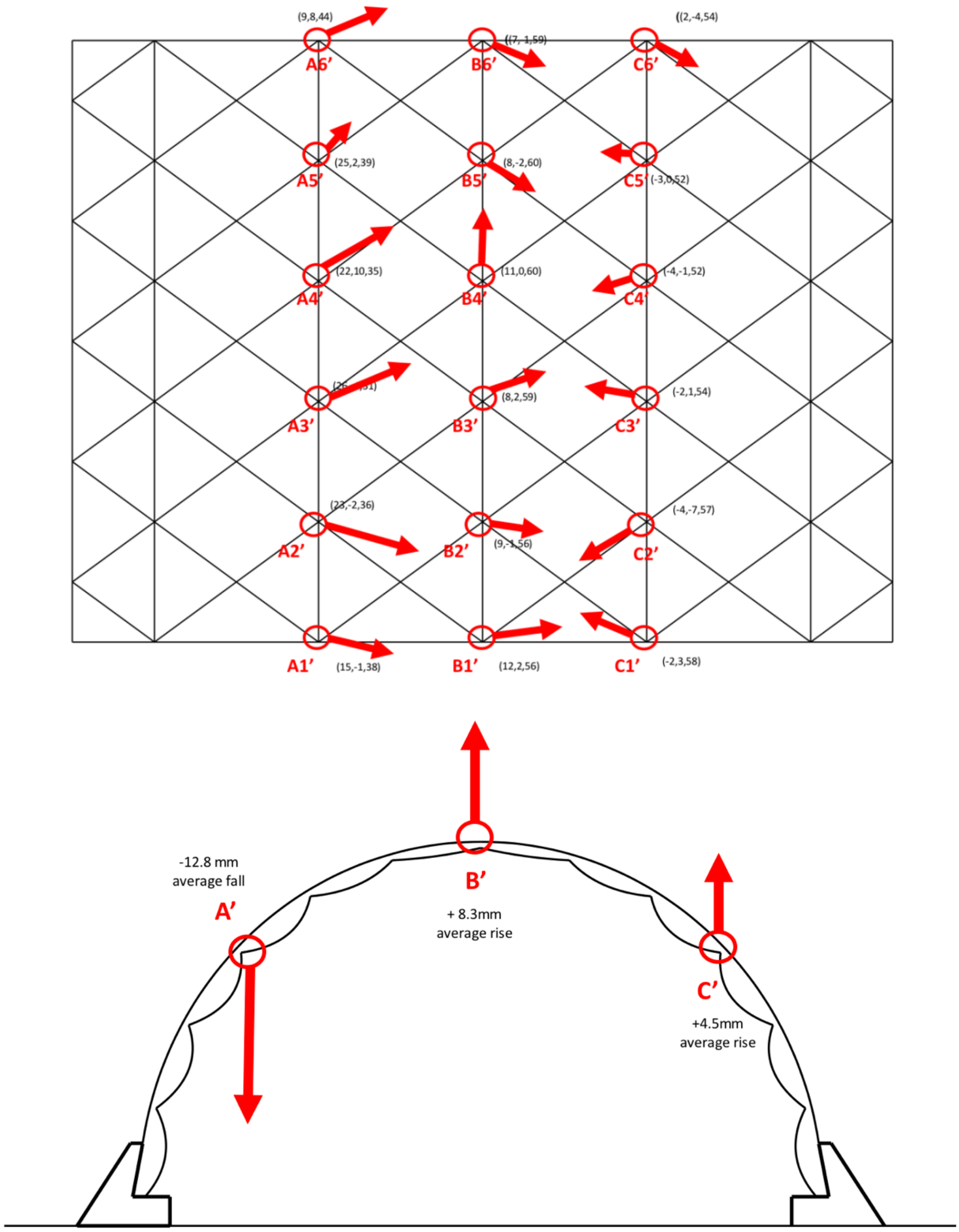


Fig. 7.29 Relative Movement of Shell 1 after casting finishing coat

Shell 1: after finishing coat

A6' (9,8,44)	B6' (7,-1,59)	C6' (2,-4,54)
A5' (25,2,39)	B5' (8,-2,60)	C5' (-3,0,52)
A4' (22,10,35)	B4' (11,0,60)	C4' (-4,-1,52)
A3' (26,-4,31)	B3' (8,2,59)	C3' (-2,1,54)
A2' (23,-2,36)	B2' (9,-1,56)	C2' (-4,-7,57)
A1' (15,-1,38)	B1'(12,2,56)	C1' (-2,3,58)

Shell 1

When the first 10mm scratch coat was applied, the apex rose. Side A went down consistently with a maximum downward displacement of 7mm whilst Side C rose and did so with a maximum upward displacement of 4mm at both edge points C6 and C1. Horizontally, region A moved upwards i.e. towards the right with points A2 and A4 registering maximum positive x-displacement of 10mm. In terms of y-displacement, A1, A2 and A3 moved 1mm towards the front edge whereas A4 moved 10mm in the positive direction i.e. to the right hand side.

After the scratch coat was allowed to settle and cure for a couple of hours, the finishing coat was applied, further movement was observed. The front region of the shell alongside A moved downwards considerably with a maximum of deflection of -19mm at points A3, with A2 and A1 registering a drop of 14mm and 12mm respectively.

The middle apex regions rose further at this instance, with points B4 and B4 registering an upward displacement of 10mm from 5mm and 6mm recorded respectively before final coat.

The final concrete layer did not result in much more movement in region C with the exception of the front region. A further upward displacement to 7mm (from 4mm) and to 8mm (from 4mm) are observed at the points C2 and C1 respectively. The remaining regions seem to remain stable after the final coat application.

Shell 2

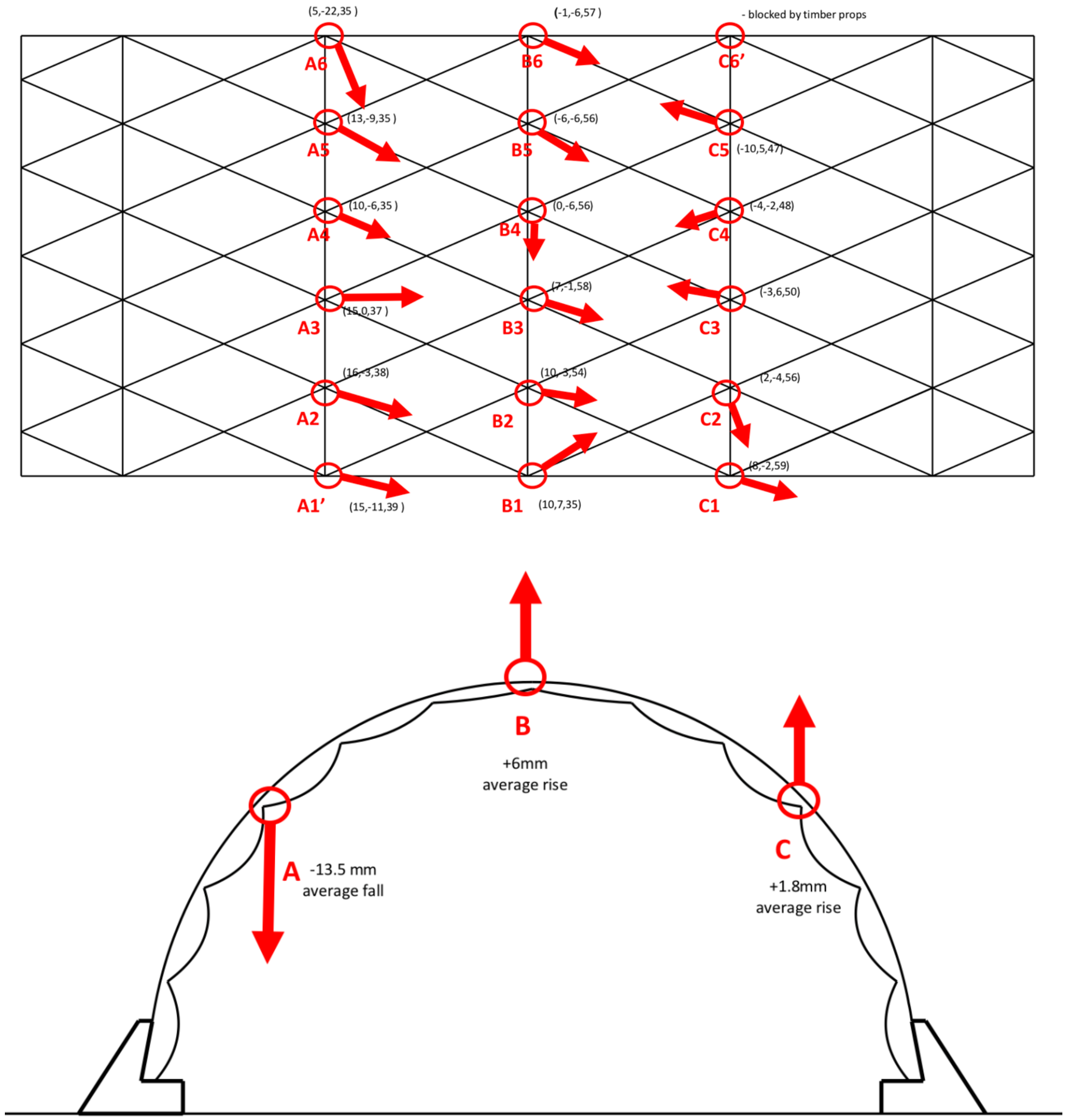


fig 7.30: three-dimensional Displacement Graphs for Shell 2 (concrete was applied in a single application).

Shell 2

A6 (5,-22,35)	B6 (-1,-6,57)	C6 (void) - blocked by timber props
A5 (13,-9,35)	B5 (-6,-6,56)	C5 (-10,5,47)
A4 (10,-6,35)	B4 (0,-6,56)	C4 (-4,-2,48)
A3 (15,0,37)	B3 (7,-1,58)	C3 (-3,6,50)
A2 (16,-3,38)	B2 (10,-3,54)	C2 (2,-4,56)
A1 (15,-11,39)	B1 (10,7,35)	C1 (8,-2,59)

Shell 2

The second shell was cast in a single application rather than in 2 stages. The general result was similar in vertical displacement patterns to Shell 1.

Region A exhibited a maximum negative displacement (drop) of 15mm registered at A4, A5 and A6. They consistently moved positively on the horizontal x-axis with a maximum of +16mm at point A2, +15mm at points A4, A5 and A6. In terms of the y-axis, all registration points have moved towards the front having been displaced negatively.

Region B (apex line) have mainly positive displacement exhibited with the exception of B1 which dropped 15mm. Points in the front i.e. B1, B2 and B3 recorded a positive x-axis displacement between 7mm and 10mm whereas points B5 and B6 at the back at -6mm and -1mm respectively.

The front points C1 and C2 of the shell have been displaced towards the right and to the front and they rose. The back points C5 and C6 with the exception of C6 (which was blocked by a timber support and therefore not able to be registered), moved negatively on the x-axis ie to the left direction. They also recorded a vertical displacement of -3mm and -2mm respectively suggesting that they have dropped marginally after concrete loading.

Construction

From the resultant shell, a strong relationship between construction sequence and final form is noticed from the construction process. The flexible nature of the gridshell formwork during casting posed a problem producing a shell of curvature of the initial gridshell despite being braced, triangulated and rigidified. This formwork system that deflected to physical pressures that trowelled concrete onto the formwork caused the structure to deflect.

In both test shells, resultant movement exhibited similar formwork movements during construction stages – in both cases, the areas A both lowered (Area A average drop to span ratio of 0.98% for shell 1 and 1% for shell 2, and whilst areas C both rose (Area C average rise to span ratio of 0.3% for Shell 1 and 0.1% for Shell 2). The apexes (area B) were raised as well. As the two shells were designed as singly curved structures, averaging the vertical movements of points along transverse lines A, B and C to understand shell movement.

Notably, this observation corresponded with the sequence by which concrete was applied – area A, area C, then area B in both cases. The method and sequence of applying concrete onto a non-supported gridshell framework is proven to be significant on the eventual curvature of the resultant concrete shell.

On a larger scale, the movable nature of this tectonic may be addressed by the use of scaffolding props strategically placed to support key points in the gridshell formwork to ensure these data retain their designed heights to achieve the desired curvatures.

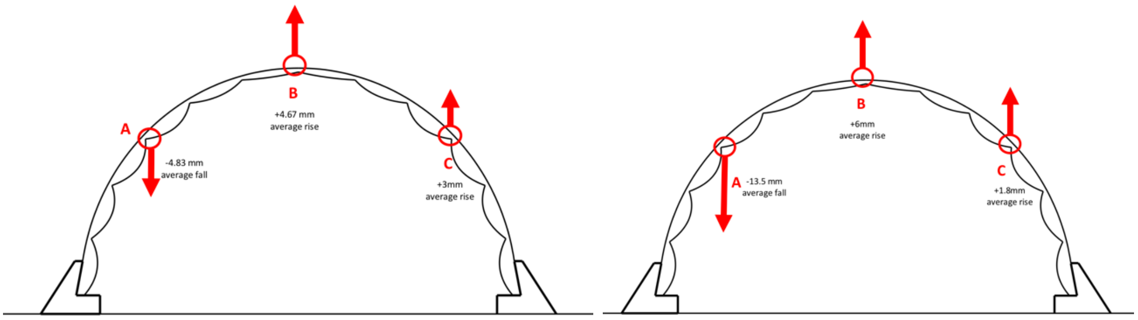


fig 7.31: Shell 1 vertical movement on left, Shell 2 movement on right.

7.3.2 Limitations of the construction exercise

- To measure the movement of shell during casting, plumb lines were used. To increase accuracy, the use of laser distant meters should have been set up to fully understand the movement pattern.

- Designed as simple vaulted shells with single curvatures in compression, the use of reinforcement is minimised and restricted to using polypropylene strips mixed within the concrete. In any actual construction for a project, steel meshes may be necessary, to be confirmed with structural engineers.

- Concrete was applied by 3 people; each using a different force on the formwork. This is difficult to control to ensure uniformity. In the past, we see concrete trowelled by hand onto firm and stiff timber boarding in the shells by Isler and Candela. Their shells were applied on hard surfaces as on wooden formwork supported comprehensively on extensive scaffolding. The issue of non-uniformity may be solved by gunniting in a uniform pressure.

7.4 Aesthetics

This technology describes a stereogeneous construction described as “an approach which considers the relationship between traces of construction and the formal tectonics for constructing architectural space, structure, surface and sculptural form (Manelius, 2012).” The use of deployable gridshells as formwork clearly implied this sequencing of construction and interaction between technologies to create a structural concrete skin that described strong stereogeneous characteristics. This construction not only discussed various elements of fabric formwork that constitutes this new technology, but imbued strong construction elements namely the use of devices of "frame" and "textile" associated to fabric-formwork

7.4.1 Patterning

The most distinct and unique aspect of the two resultant shells is the appearance of concrete cushions created by concrete suspending between grid laths. This is the direct consequence of the use of construction technologies. Firstly, patterns displayed indicated the way it was constructed. The construction clearly expressed the use of a frame upon which fabric was stretched to receive a thin layer of concrete. The lines inscribed on the surface imprinted the pattern of the gridshell, namely gridlath and bracing. The aesthetic and structural qualities of fabric can influence qualities of these cushion surfaces.

Above all, the appearance of dominant lines was observed. These lines run in the direction of the uppermost grid laths which is in closest contact with the concrete. The aesthetics of the shell was therefore highly indicative of the construction technology used. Fabric texture is imprinted in the finished concrete shell.

fig 7.32: Fabric textures and gridshell formwork are imprinted on the undersides.

Fig 7.33: Cushions are formed on the shell undersides.

The eventual shape and leaning of the shell was informed by the sequence and method of concrete application. The construction experiments demonstrated how deflection susceptible the gridshell can be when subjected to forces during concrete application.

The idea of gridshell as frame is instrumental to the use of fabric formwork technology in this particular arrangement. In this case, concrete walls and columns require a frame onto which to suspend the textile shuttering. This notion of the frame complements the combination of fabric formwork use, as textile shuttering requiring substantial framing onto which fabric is suspended.

The resultant cushions are referential to the recent experimental constructions of form efficient beams by Dr Daniel Lee at University of Edinburgh (2011). The appearance is similar to the imagined underside of Lilienthal's fabric suspended floors, although no photographic evidence of their exposure to the floor below was available.

7.4.2 Edges

In shells, the free edges allowed designers to construct an illusion of thinness that was not applicable to rest of the shell. The illusion of shells appearing thinner at their edges is observed as a perennial aesthetic pre-occupation by designers of shells such as Heinz Isler and Felix Candela which suggested an aesthetic value of thinness (or an illusion of it) as a aesthetical virtue.

In this exercise, the construction of a gridshell from elliptically profiled hollow pvc tubes offered the opportunity to not only express the construction at their free edges, but used the same material to maintain a consistent language. The use of pvc conduits of the same dimensioned profiles defined a crisp and sharply-defined free edge (fig. 7.43) illustrating what could be achieved at this scale. It also suggests a detail that employed the same material as the main gridshell for tectonic consistency. In this case, an edge detailing accentuated the thinness should be read as an honesty to tectonic rather than an intention to deceive and create a false impression of shell thinness.

7.4.3 Difference of appearance between underside (interior) and upperside (exterior) of the shell.

Liken to how Candela expressed timber board-markings in his concrete shells, shell upperside surface treatment differed from the under surface. This contrast in textural expression is distinguishable. Board-markings appeared on the underside of the concrete shell - whilst the upper/ outside surfaces appeared smooth. This duality of textures is the result of different techniques/ technologies. Here, an opportunity for fabric to impact on concrete form and surface could address the philosophical concerns raised about the aesthetic of concrete by Miguel Fisac (chapter 4.9.1). Whilst dependent on formwork technologies and process, concrete materiality develops a new language. Not only is structural performance (to be discussed in the following section) relevant, this method of construction redefines structural and aesthetic use of technology. Whilst fabric suggests the possibility to borrow material qualities, different forms can also be achieved as hydrostatic pressures is adjusted to vary dimensional changes in cushion depths and textures.

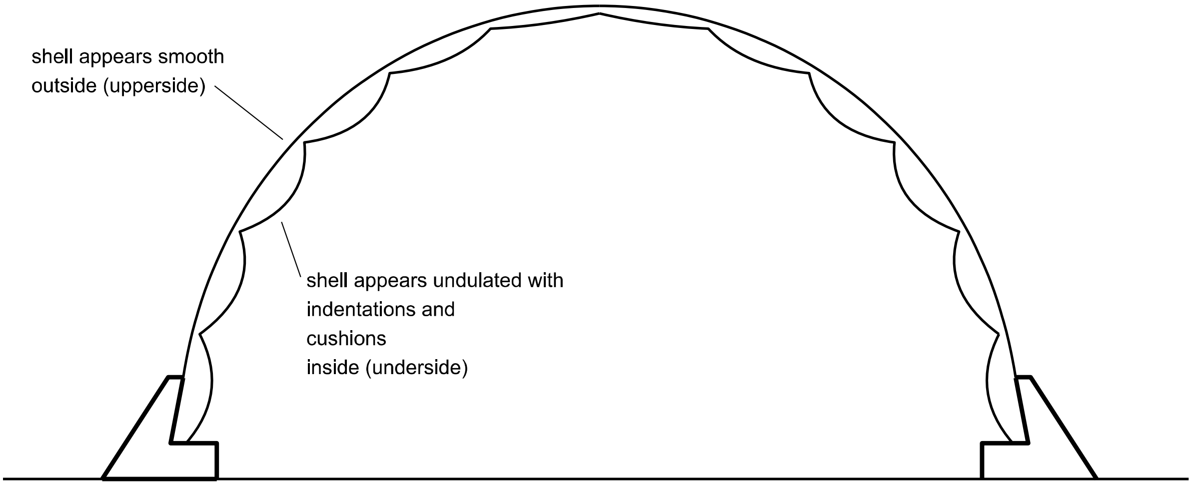
fig 7.34 Candela's shells expressed the method of construction with board markings on the underside of the shell where the concrete sat upon. The upper surface is smooth faced.

Fig 7.35: The underside of the shell contains cushioning with dominant lines indicating uppermost lines of the gridshell lath direction. The upperside, like Candela's shells, are smooth.

Inside, the cushions is honest to the construction method. The undulation of the shell is not expressed on the outer and upper surface. Here, the continuously curved outside surface allows precipitation run off, a practical point in roof design in most climates. This was not a problem to Felix Candela who worked in Mexico City which experience little precipitation hence eliminating key roof draining functions. If the Church of Our Lady of the Miraculous Medal was situated in UK, indentations (fig 7.37) will become problematic for precipitation egress.

The idea of the outside surface that accurately follows the curvatures of internal spaces can be seen in the 2013 workshop experimentation with concrete canvas (fig 7.44) where the underside of the concrete canvas shell closely replicated the upperside, especially when seen from the outside. In building projects, the thinness will have practical implications on their use.

The cushions appear deepest at the abutments whilst cushions at the apex are less pronounced and even. A large concentration of air pockets and pvc reinforcement strands were visible, suggesting a air not escaping from fabric surface, partly due to the dry mix used.



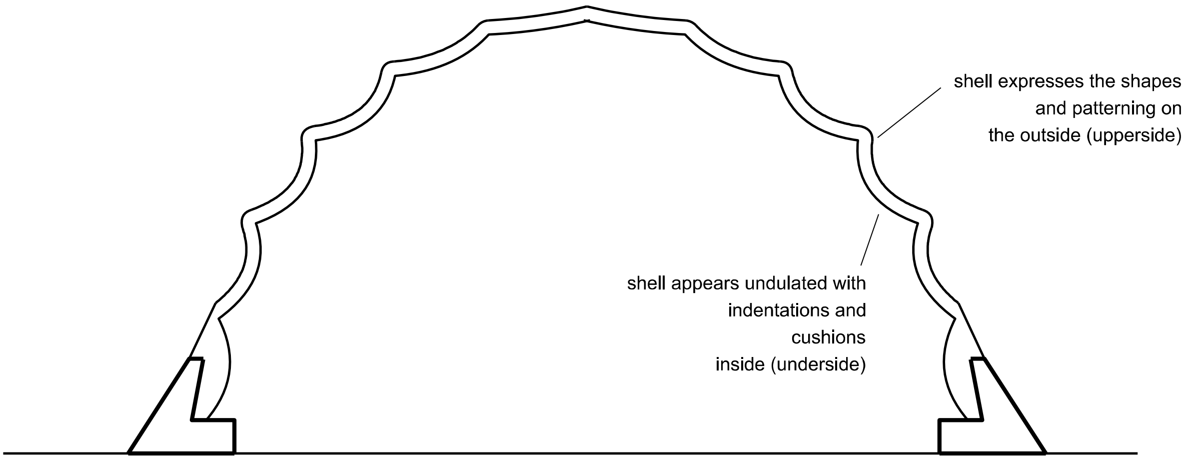


Fig 7.36 a) top: The expression of resultant concrete shell is different seen from the inside (underside) from the outside (upperside). b) bottom: The concrete shell maintains a consistency in terms of expression- an even thinness in turn produces an external appearance consistent with an internal tectonic but depends on the context the project is situated.

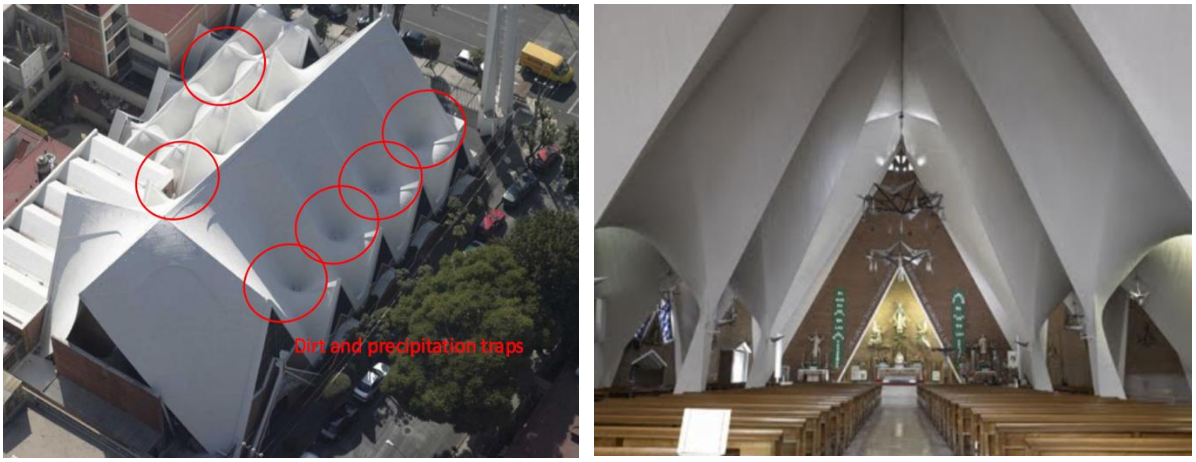


Fig 7.37 Candela's Church of the Our Lady of the Miraculous Medal, Mexico City 1955 portrays a shell of even thickness giving a representative depiction of the space enclosed by the shell suggested by its exterior.

Fig 7.38: Cushioning Effects – patterns are determined by the lowest layer of gridshell formwork.

Fig 7.39 Concrete detail of the underside of the shell

fig 7.40: Cushioning Effects – patterns are determined by the lowest layer of gridshell formwork.

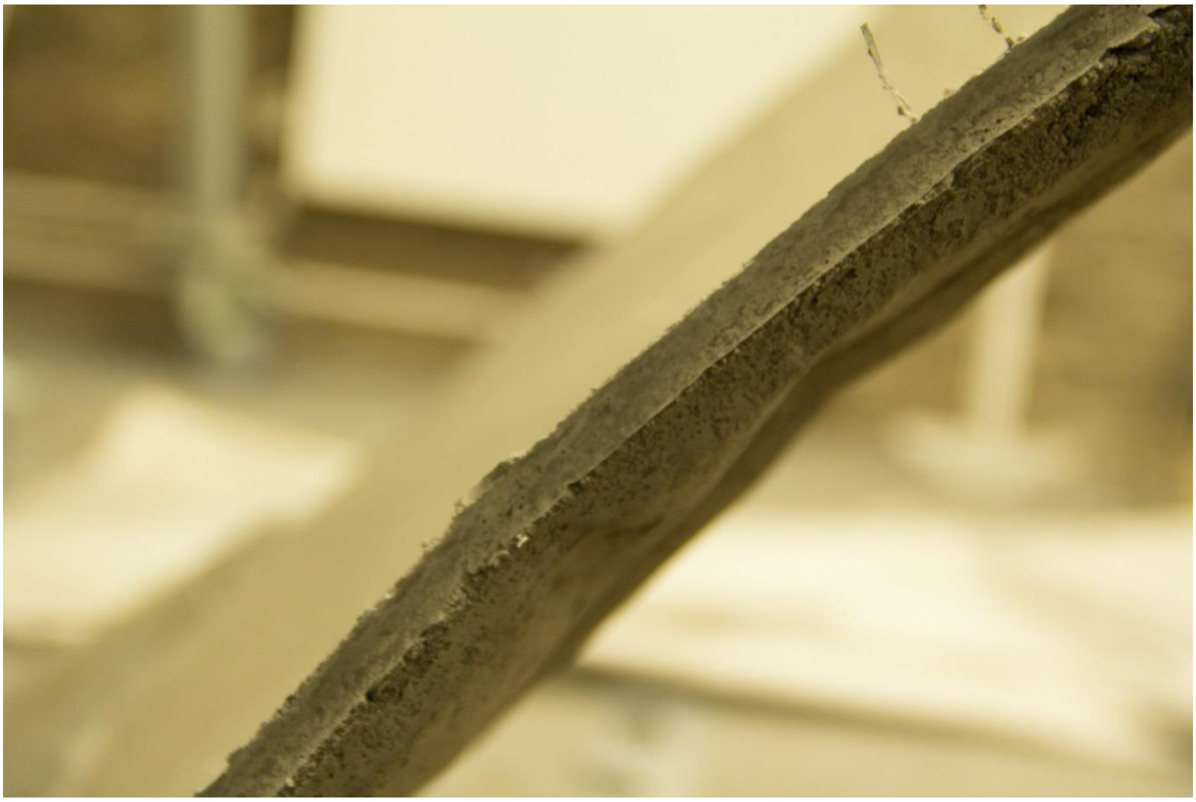


fig 7.41: Edge details accentuate the edges using the same components as the formwork materials.

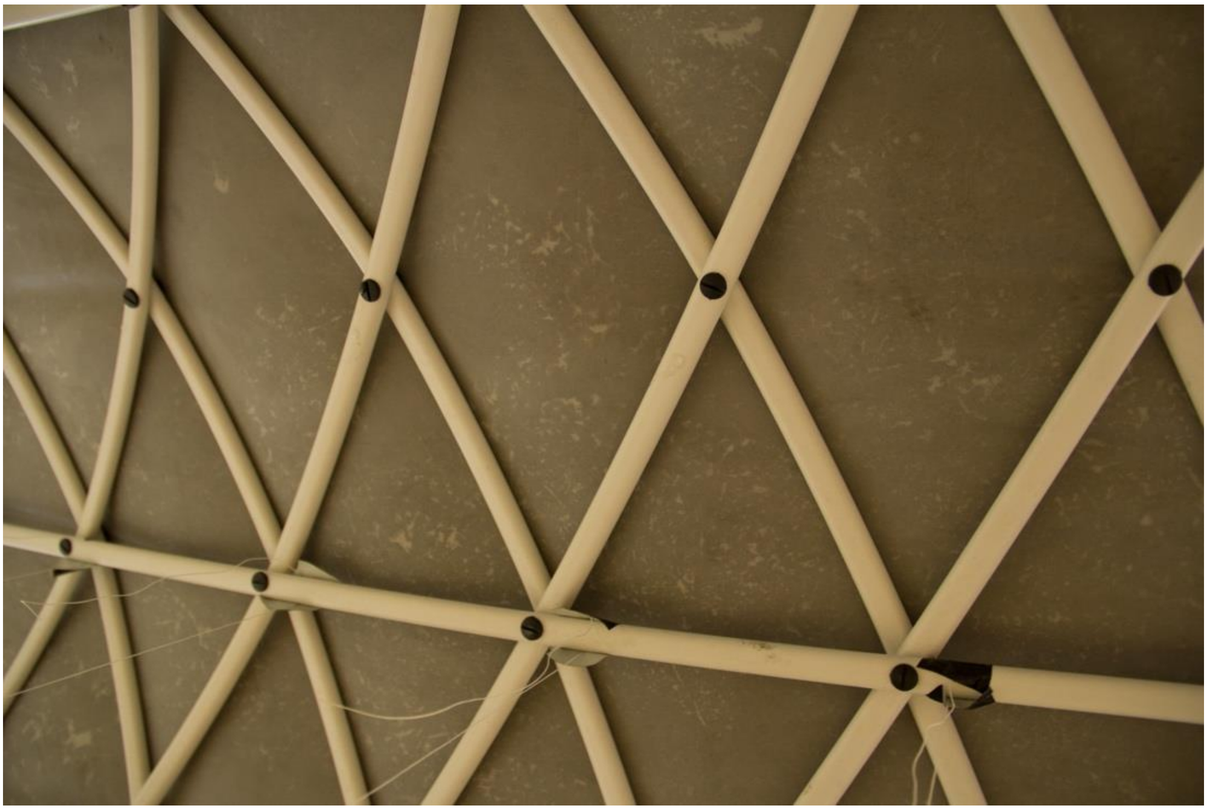


fig 7.42: Cushioning Effects – patterns are determined by the lowest layer of gridshell formwork.

Fig 7.43 Thinness of the shells at the edge

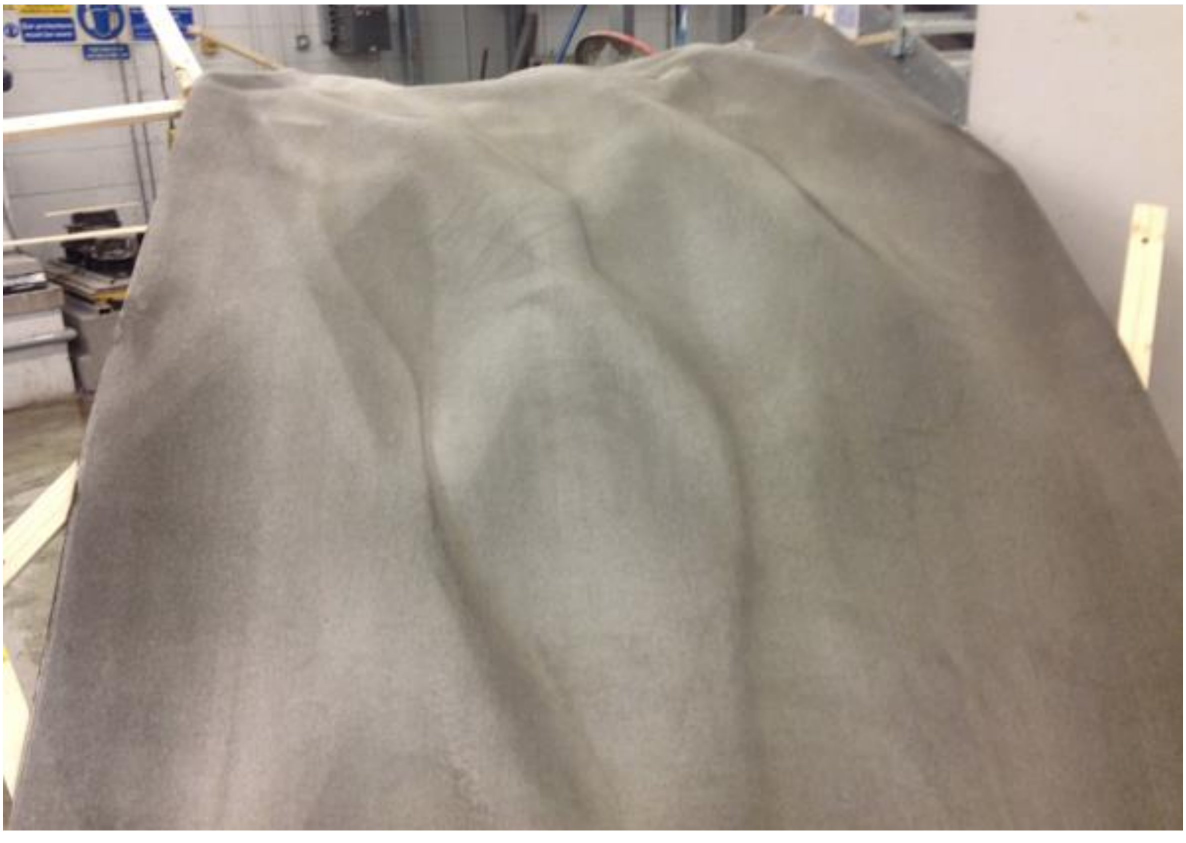


Fig 7.44 Concrete Canvas experiments in 2013 produced a shell that expressed a true representation of the surface underneath described similarly on the upperside due to uniform thickness.

7.5 Structural Analysis

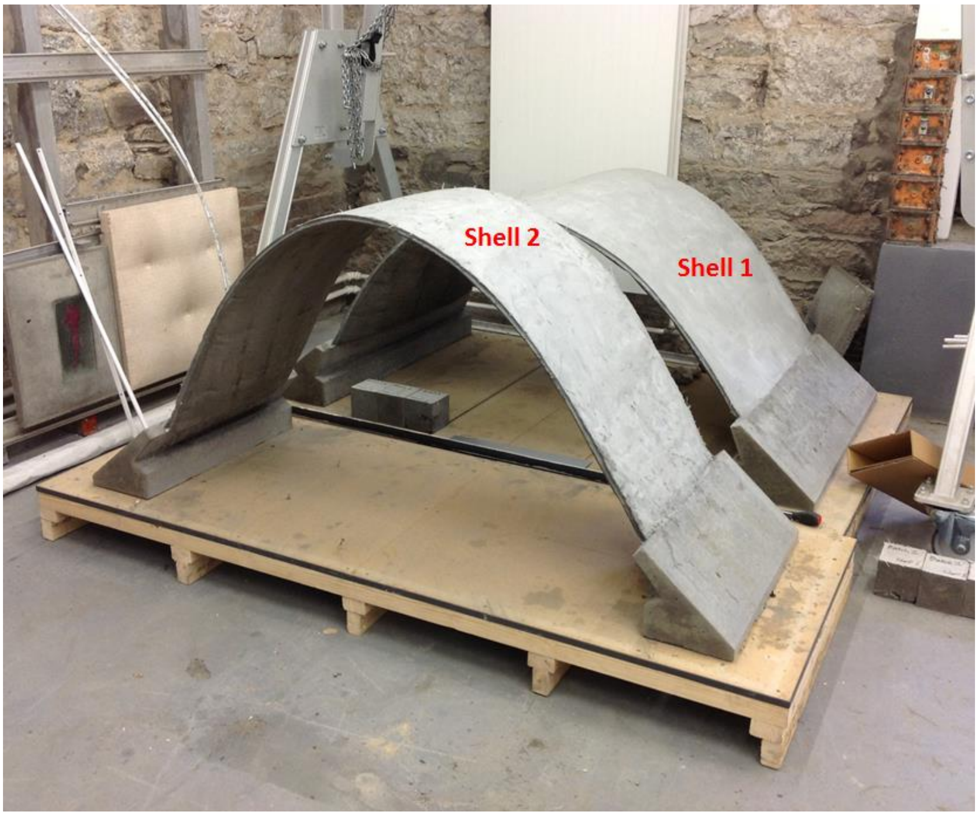


Fig. 7.45 Shell 1 and 2 when placed side by side

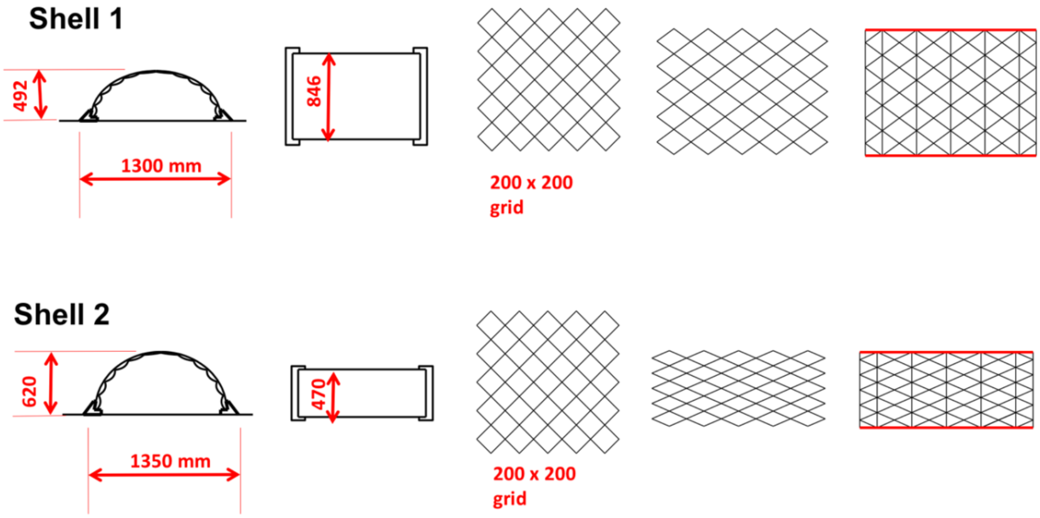


Fig. 7.45 Shell 1 is wider and shorter of the two shells.

Shell	Span/ mm	rise/ mm	**Span to rise ratio**
1	1300	492	2.64
2	1350	620	2.17

Fig. 7.46 Shell 1 and 2 Span to rise ratios.

The construction exercise has proved the possibility to create concrete shells by using the same deployable and actively bent gridshell as formwork to reconfigure concrete shell pours. However, their process was uncontrollable resulting in concrete shells with a vertical movement of 5.8 % (i.e. 29mm / 492mm) height variation for Shell 1 and for Shell 2: 3.8% (24mm / 620mm) . The dry mix has resulted in large variations between indentations and cushioning due to the force that was needed to depress concrete into the formwork. This next section investigates the structural capabilities of the two concrete shells cast to gain a precise geometrical and structural understanding of the Shells 1 and 2.

This section is based on the work undertaken by two Masters in engineering students (Marcin Dawydzik and Marta Walejewska in 2015) who analysed the shells with the aim to answer the following questions:

- What is the geometry and shape of the resultant concrete shell
- How strong is this concrete shell?
- How stiff is this concrete shell?
- What is the failure mode of the concrete shell?
- What is the failure behaviour of the shell.

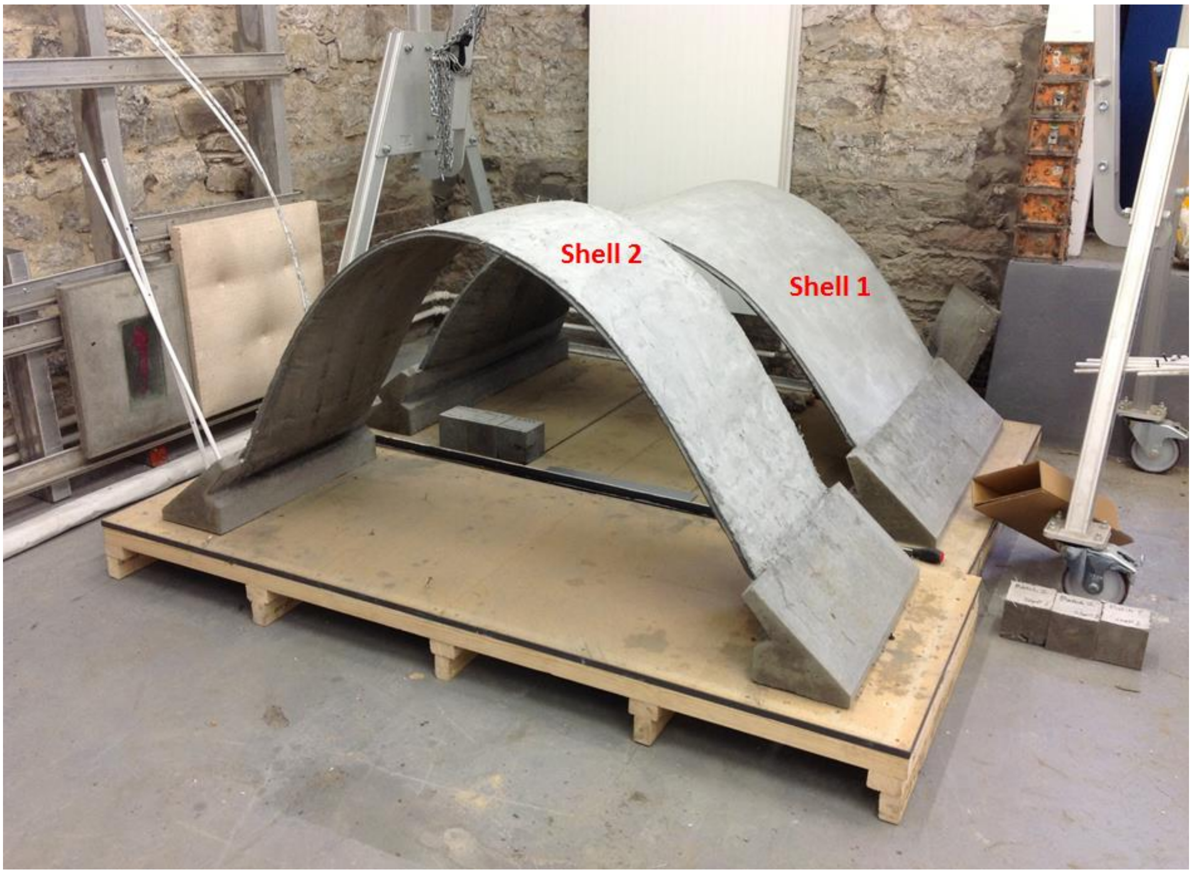


Fig. 7.47 Shell 1 is wider and shorter of the two shells.

To address the above questions, structural performance of the shells is carried out:

1. To understand the discrepancy of the shell dimension and shell shape differing from the perfect form, the resultant shells are measured, recorded and results plotted to understand the precise geometry of the shell. This is important as the gridshell formwork recorded movements during casting and this may have a structural impact on the resultant concrete shell performance.

2. Unlike previous shells which have a generally even thickness, particular to this proposed method of construction, with concrete cushioning, thickness variations are measured to understand the true form of the shells.

3. These data/ information are entered into a finite element model which analysed the model to an array of loading conditions.

4. Shell deflection within the elastic range is conducted to understand deflection behaviour.

5. Finally, the shells are tested to failure to gain an understanding of failure mode and failure capacity.

7.5.1 Shell Geometry

An initial visual inspection was conducted. Both shells exhibited a slight saddle shape where the middle of the apex fell slightly lower than the sides (free edges). To study, record and understand the surfaces systematically, a jig was used to measure and precisely plot the surfaces of the top surface of the two shells. A process of recording this without using expensive photogrammetry was carried out by setting up a jig illustrated below. This was the same method that Heinz Isler used to measure vertical distances of his shells to check for geometrical accuracies (Chilton, 2000).

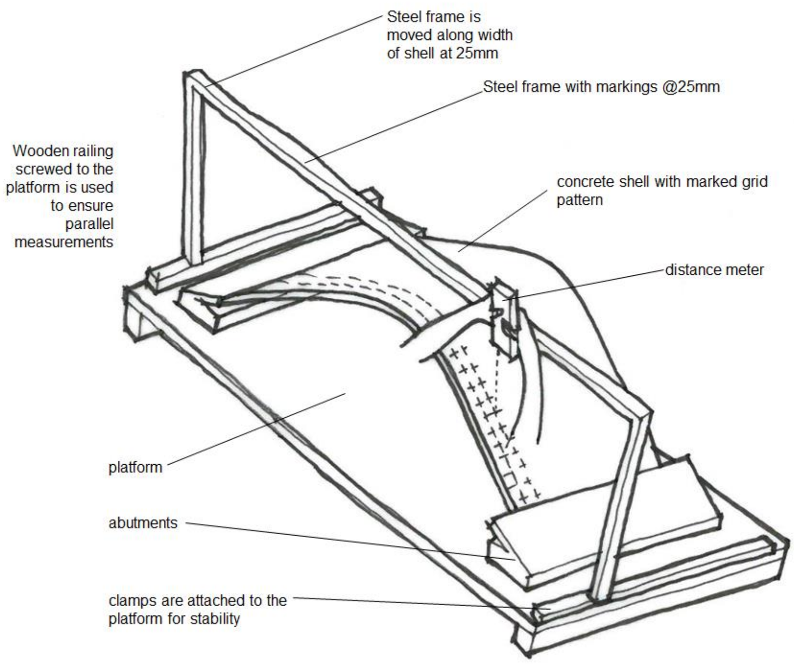


Fig 7.48 Geometry Measurement process

7.5.1.1 Upper surface measuring procedure:

To take accurate measurements of the upper surfaces, a steel frame was made up. It was welded from 25mm x 50mm rectangular tubular sections straddling longitudinally along the shell clamped to a wooden railing secured to edges of the wooden base on the short sides (fig 7.48). A digital distance meter was used to take measurements of the distance from the steel rail at 25mm distances projected onto the shell on plan, yielding distances with high accuracies. The steel frame was moved to record the next data row. These data were then entered into Excel and FE software to understand the exact upper surfaces of the 2 concrete shells. Results are presented in appendix A.

7.5.1.2 Results

With the data plotted, the respective shell sections confirmed that the upper surfaces of both concrete shells were indeed not uniform and had a degree of variation in the vertical dimension.

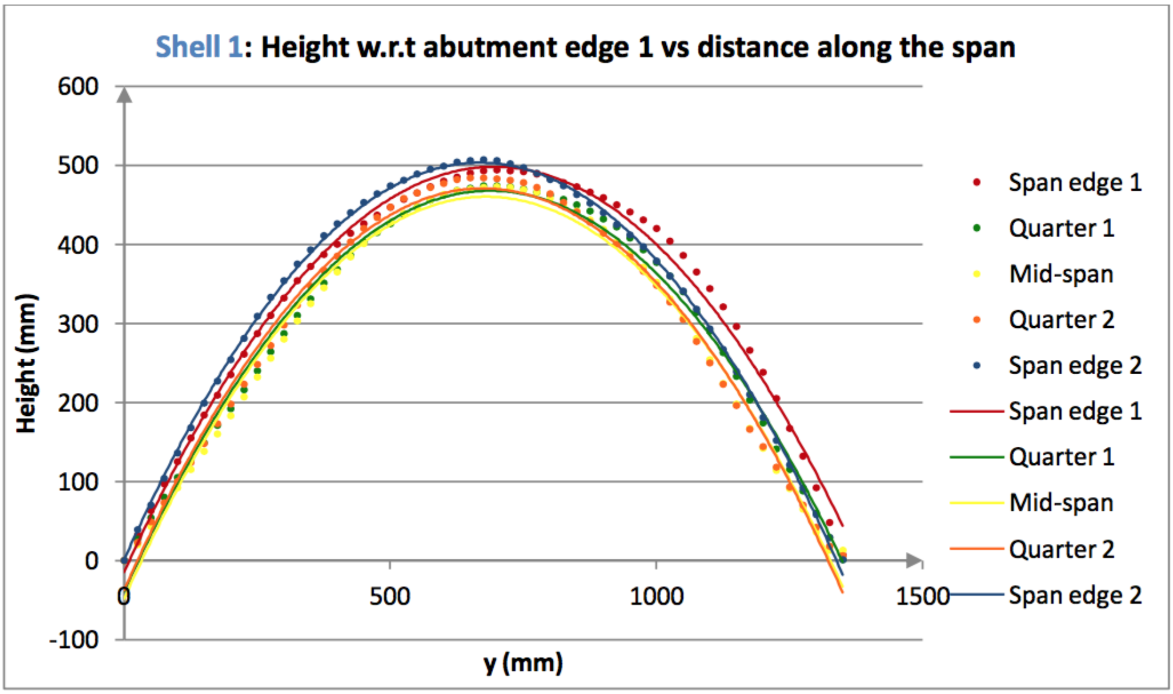


Fig 7.49 Shell 1 With the datum (0mm) set at the various points along Abutment Edge 1 (see figure 7.50), the variation of longitudinal points along shell span are plotted to produce a chart that describes the relationship of height difference relative to abutment edge 1 vs distance along the span. (courtesy of Walejewska, 2015)

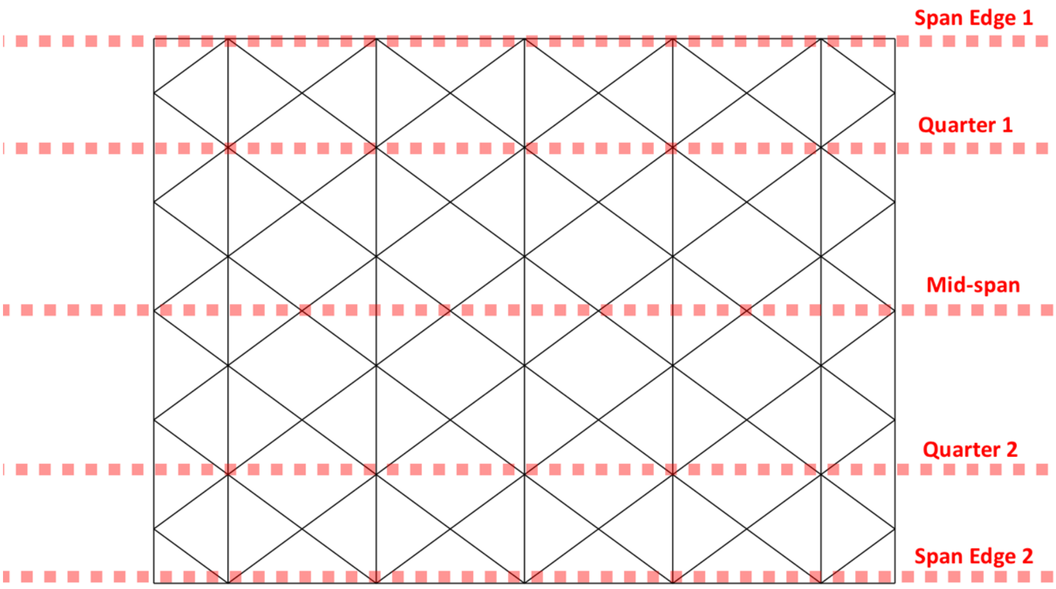


Fig 7.50 Shell 1 Key Plan (not to scale)

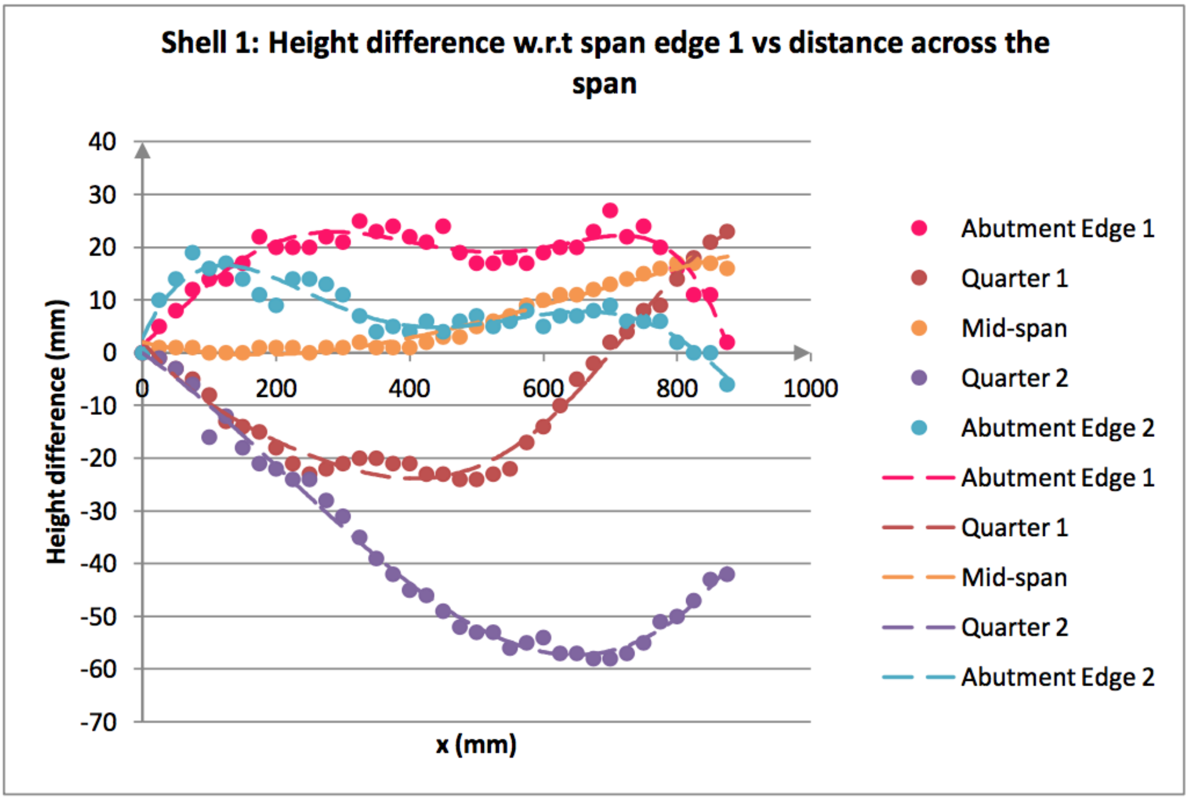


Fig 7.51 Shell 1 With the datum (0mm) set at the various points along Span Edge 1 (see figure 7.52), the variation of transverse points along the transverse dimensions are plotted to produce a chart that describes the relationship of height difference relative to span edge 1 vs distance across the span. (courtesy of Walejewska, 2015)

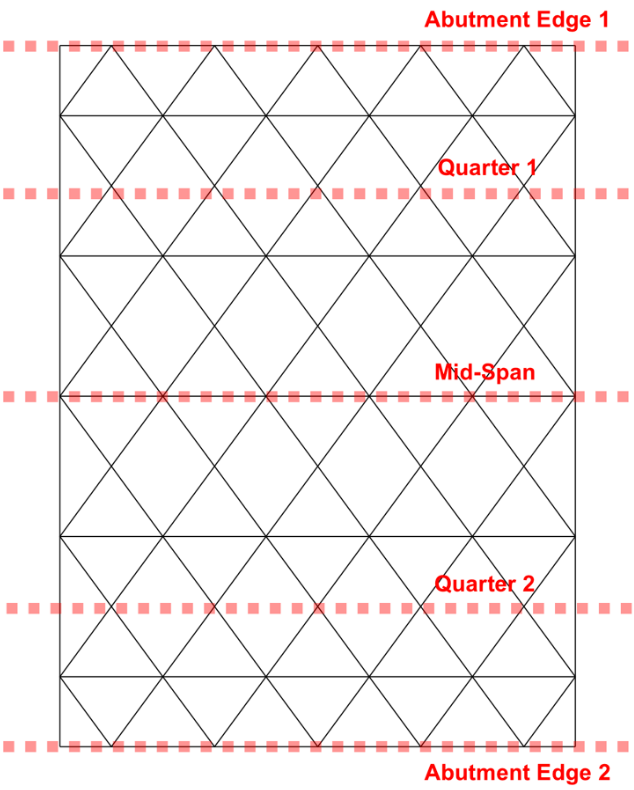


Fig 7.52 Shell 1 Key Plan (not to scale)

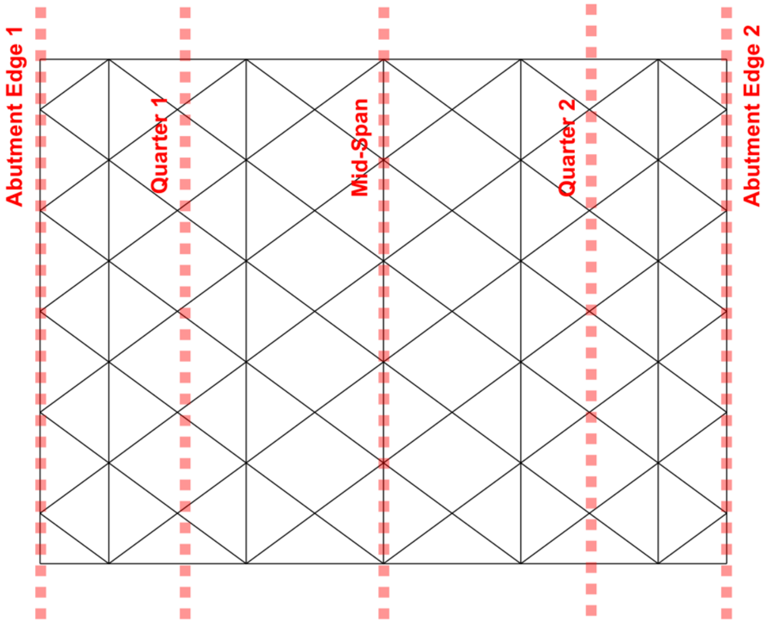


Fig 7.53 Shell 1 Key Plan (not to scale) rotated to correspond to schematic section below

Quarter 1 = A'
Midspan = B'
Quarter 2 = C'

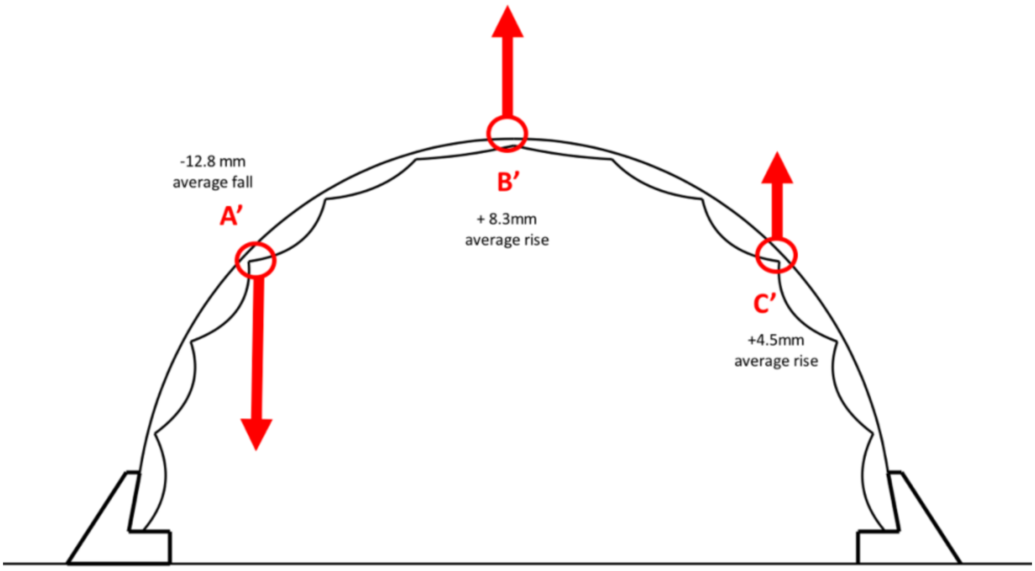


Fig 7.54 Shell 1 Key Plan (not to scale) partially corresponds to the gridshell movement during casting. Quarter 1 is found to fall to lower than the datum point set at abutment edge then rise up to 23mm above datum. Quarter 2 has fallen completely below the datum level and does not correspond to the rise in C'. This demonstrates the uncontrollability nature of this construction.

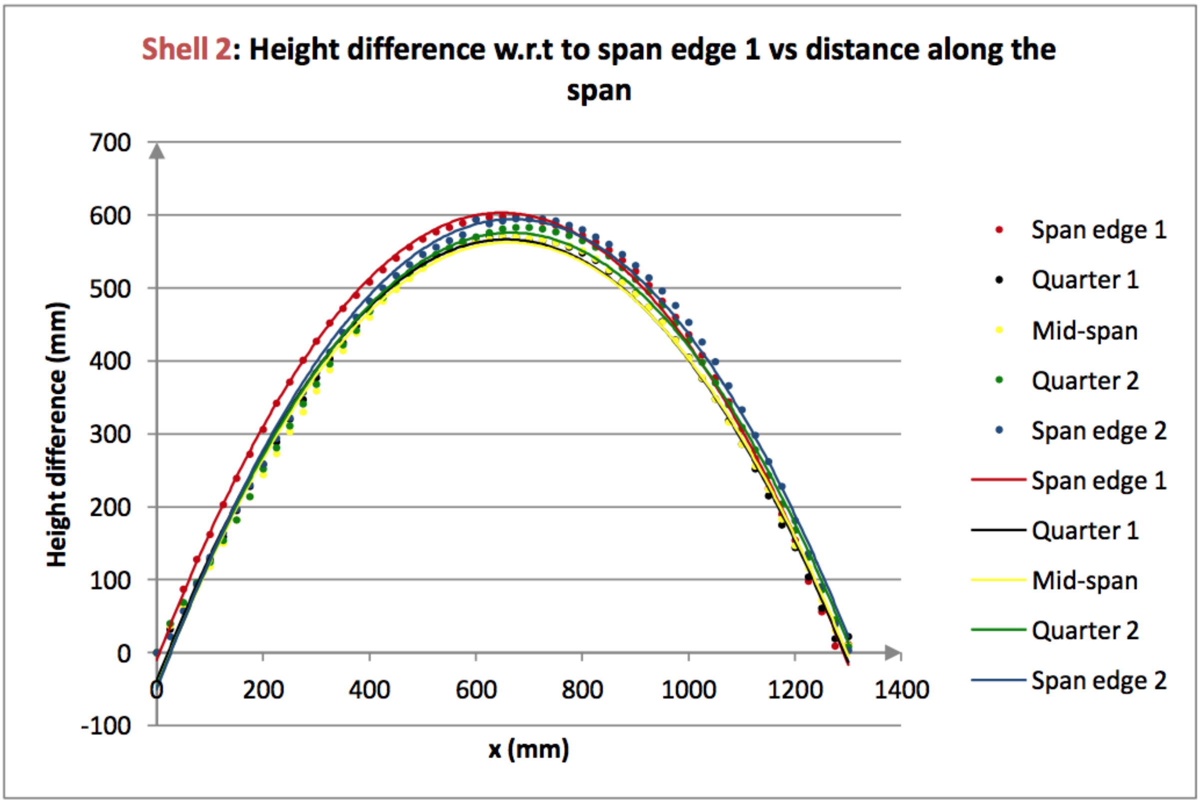


Fig 7.55 Shell 1 With the datum (0mm) set at the various points along Abutment Edge 1 (see figure 7.56), the variation of longitudinal points along shell span are plotted to produce a chart that describes the relationship of height difference relative to abutment edge 1 vs distance along the span. (courtesy of Walejewska, 2015)

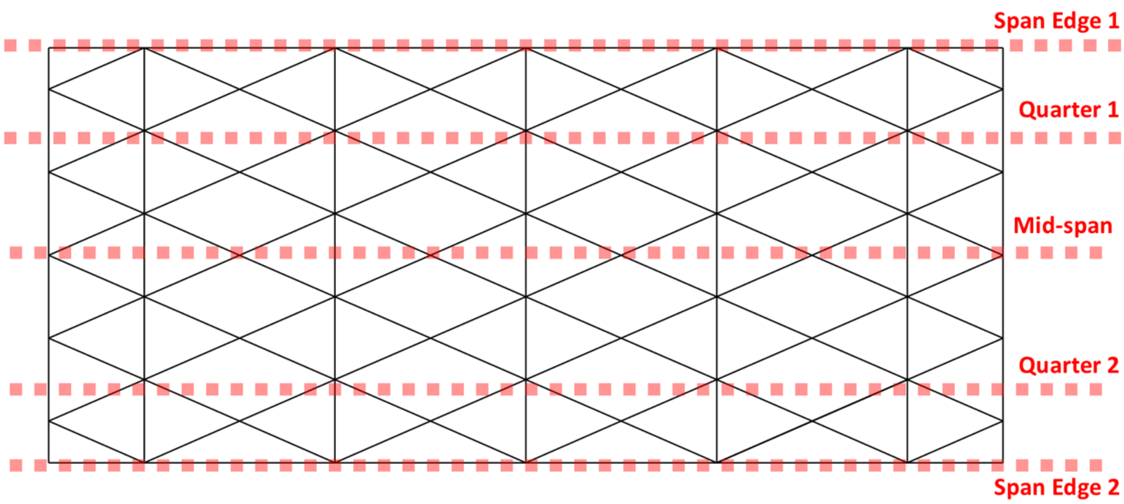


Fig 7.56 Shell 2 Key Plan (not to scale)

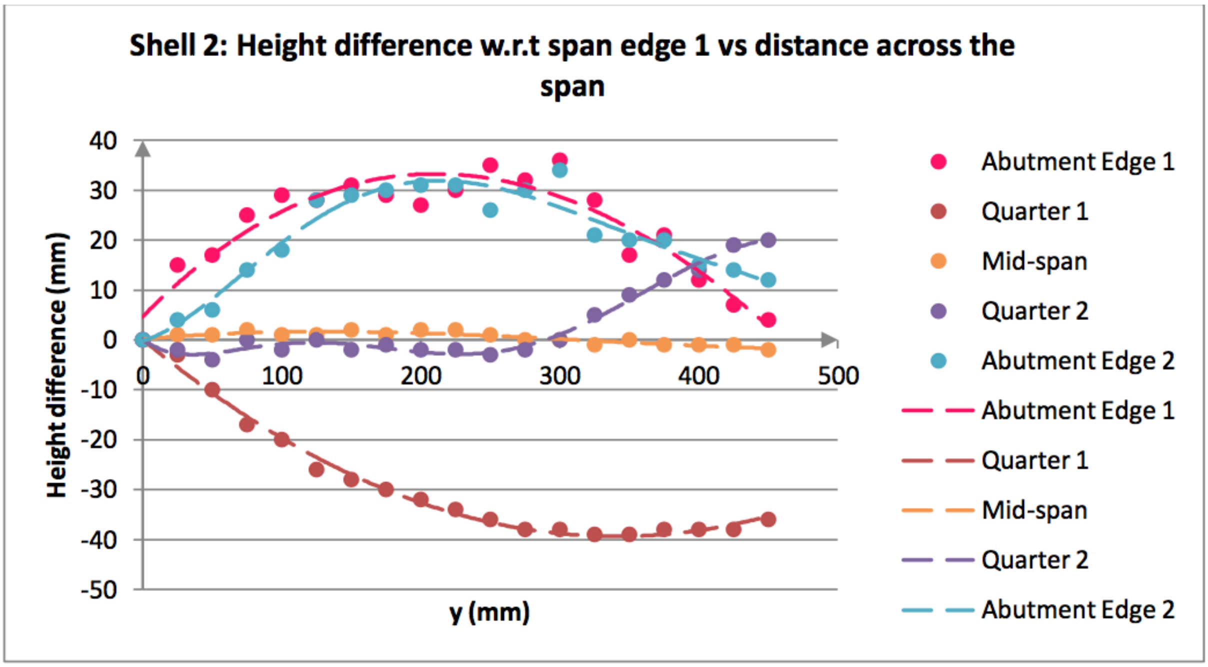


Fig 7.57 Shell 1 With the datum (0mm) set at the various points along Span Edge 1 (see figure 7.58), the variation of transverse points along the transverse dimensions are plotted to produce a chart that describes the relationship of height difference relative to span edge 1 vs distance across the span. (courtesy of Walejewska, 2015)

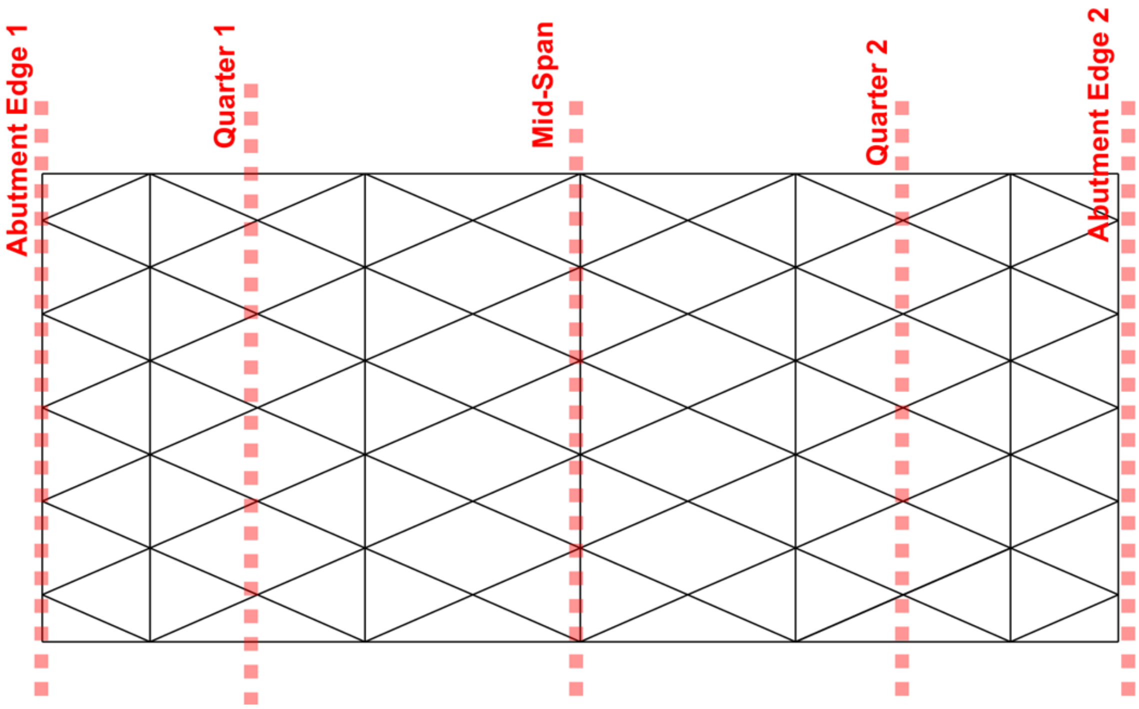


Fig 7.58 Shell 2 Key Plan (not to scale)

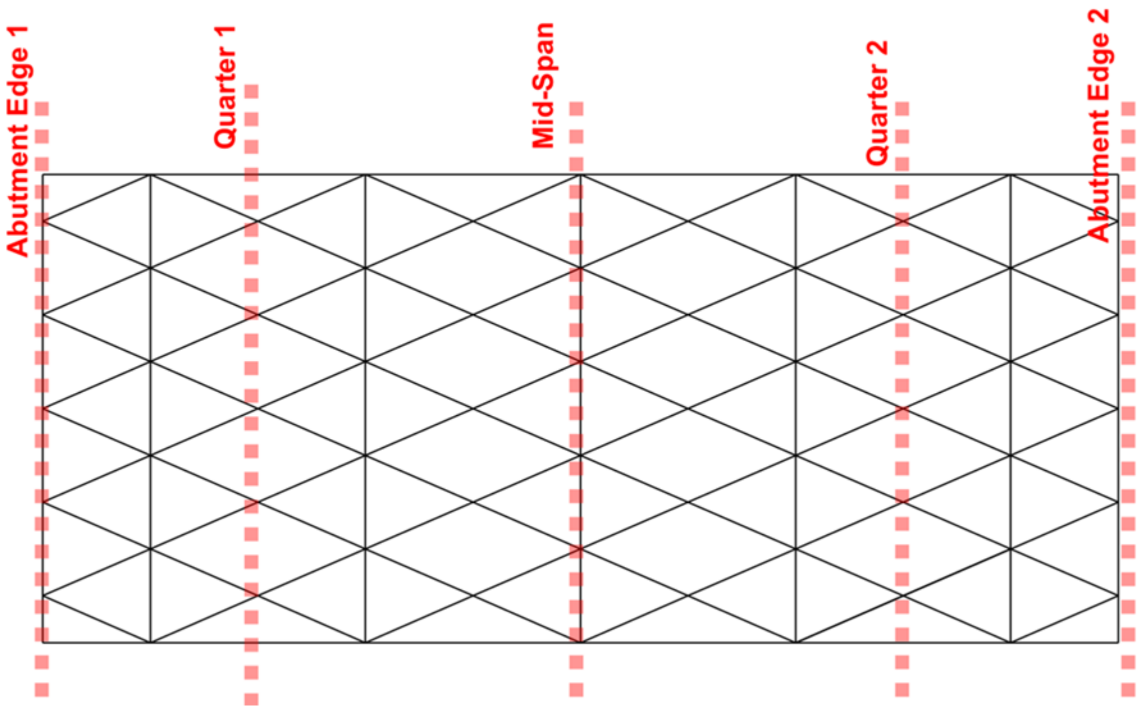


Fig 7.59 Shell 2 Key Plan (not to scale) rotated to correspond to schematic section below

Quarter 1 = A

Midspan = B

Quarter 2 = C

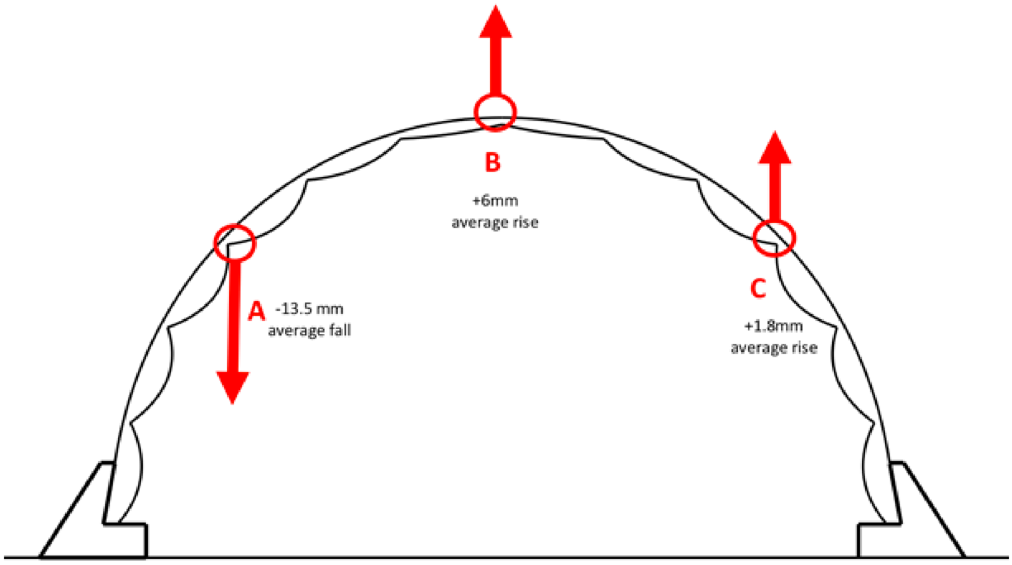


Fig 7.60 The movement of Shell 2 corresponds to the movement of the gridshell formwork more. In Quarter 1, represented by A in the section, instead of a section that is horizontal, it has dropped away. At mid-span, represented by B, the gridshell moved upwards by 6mm on average whilst the concrete shell displayed a very flat level across the shell. At quarter 2, represented by C, concrete shell section appears to be flat first and then rise upwards.

7.5.1.3 Evaluation and Discussion:

Relationship Between Eventual Shell Shape And Gridshell Formwork Movement.

The eventual geometry of upper side of the concrete shell surface largely co-related to gridshell movement during construction. The upward movement of gridshell formwork has resulted in the concrete shell displaying a corresponding rise in geometry. A fall in gridshell formwork has also resulted in a fall in concrete shell geometry.

However, this is not generally true for all cases. The height difference chart fig 7.51 showed the upper surface of the concrete falling away to the region of 60mm before rising up again to 40mm below datum. The movement at Quarter 2 for the gridshell formwork moved upwards on average. This observation does not correspond to movement pattern and is explained by the variation of the concrete thickness.

Across Shell 1, significant variations measurements were observed to be varying from 4mm to 81mm with an average of 38.27mm. Shell 2 differences ranged from 2mm to 64mm, averaging 31.75mm. It can be seen that both upper surfaces of the concrete shells exhibited saddle shapes, with Shell 1 displaying a more pronounced sagging. For both shells, there appears to be minimal discrepancies at mid-span in other words at the apex of the shell. It appears that the mid-span apex had the least difference, therefore the flattest level. The largest dimensional variation occurred at the quarter span region. This is attributed to this area being least stiff and most susceptible to hand motion pressing downwards onto the flexible gridshell formwork which also was weighed down by the deadweight of the concrete.

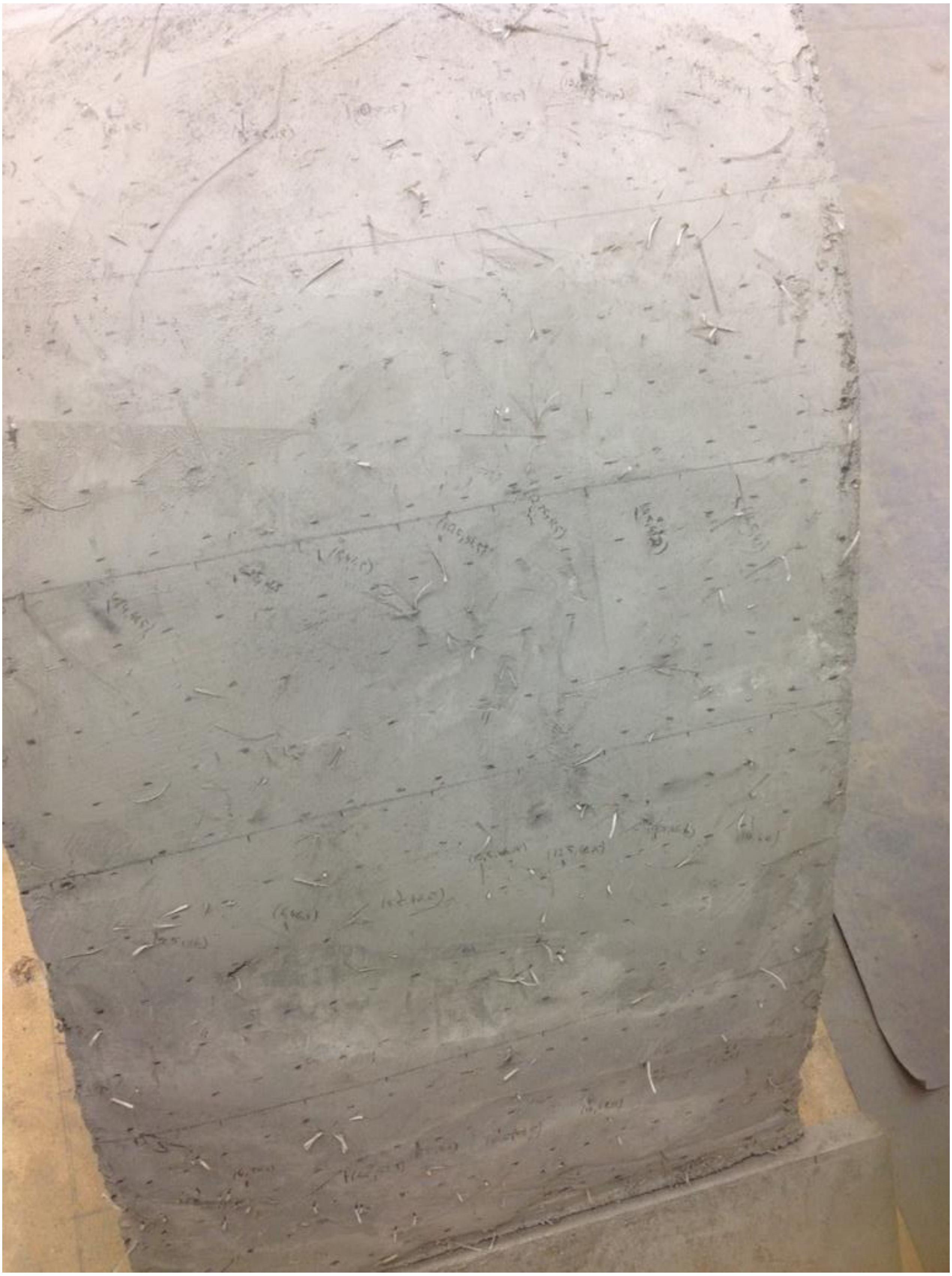


fig 7.61 shows all 1003 points drawn on the upper surface of the shell where each vertical distance was taken from the disto-meter supported by the metal frame that travelled across the shell 2.

Discrepancies

A carefully systematic measurement of points of the shell has revealed dimensional discrepancies in what appeared to be a uniform vault. There are a number of reasons why this was the case:

Inaccuracies and human error

Moving a laser tape measure along the railing was also subjected to unavoidable human error because it was very hard to keep the tape measure vertical to get an accurate reading.

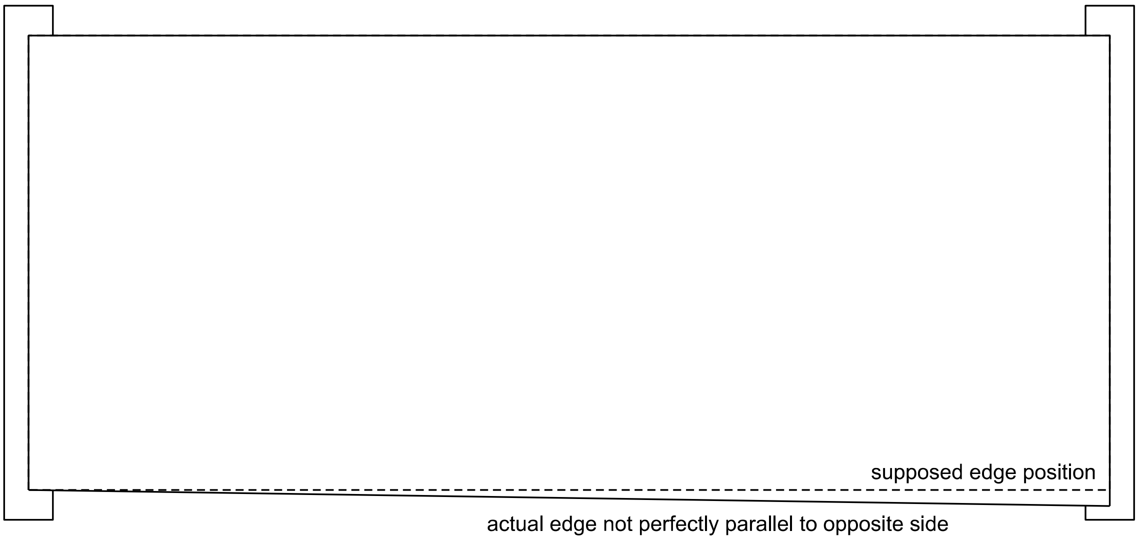


Fig 7.62 Schematic Plan Diagram explaining eccentricities in Shells 1 and 2

During the measuring process, it was difficult to align the grid points symmetrically between the 2 concrete abutments as the shells were not perfectly parallel (see fig 7.62). As such, both shells do not possess perfectly parallel straight edges for measuring. It was therefore impossible to record an accurate perpendicular cross section given the equipment available.

The process of concrete construction involved "depressing" concrete onto the lowest area adjacent to the abutments first, followed by concrete at the apex of the gridshell which was stiff in both shells, then the regions that joined the two areas together i.e. at quarter span areas illustrated in fig 7.63. In both cases, dry concrete mix was used to prevent concrete slumping and slipping on the smooth surface of the fabric. The dry mix was visible in the heavily pock-marked quality of the final concrete surface exposed on the underside of the concrete vault shell. With this dryer mix, it meant that the pressure of application had to be increased as the concrete, being less viscous, had to be pressed harder onto the formwork, resulting in unevenness in the upper surface of the concrete vault.

In addition, the fabric formwork formed "pockets" in the concrete shell as it gets filled with concrete. Creating a perfectly smooth upper surface was challenging. An alternative method will be to apply concrete in layers with gunnite (sprayed concrete), of equal thickness such that undulations of the fabric concrete were visibly expressed on the outside. However, with the use of concrete forcefully sprayed onto the flexible fabric and gridshell formwork, there might be issues of formwork rebound.

The rigidity of the fabric formwork and alternative methods of concrete application could be further improved.

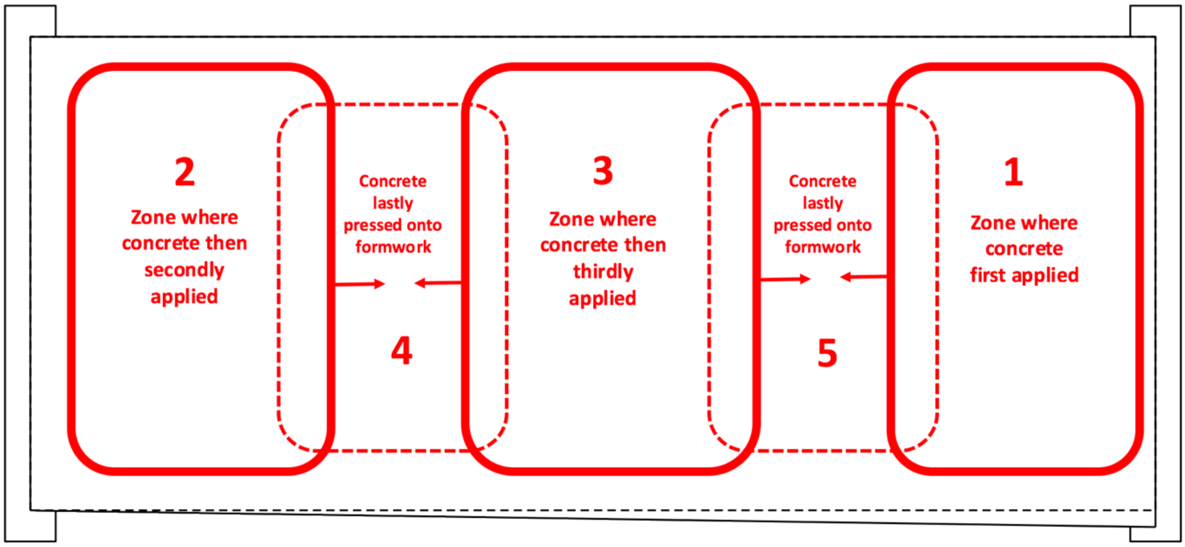


fig 7.63: sequence by which concrete was applied onto formwork: areas 4 and 5 are the most uneven surfaces

Whilst the smallest height differences across the shell were observed at the apex, the largest differences appeared at quarter span regions for both shells. As the quarter span areas were the last sections to receive concrete, much concrete was trowelled in a downward motion from higher areas and others were applied upwards from the lower areas. With the meeting of the two zones, the quarter spans were most difficult to control, resulting in biggest height variations across the concrete shell.

Due to manual hand trowelling, without propping at key points, the production of a perfectly symmetrical surface was challenging as the gridshell was constantly moving with each stage of concrete application as seen in earlier chapters.

The exercise demonstrates a construction technology of a flexible formwork which is also responsive to the application of concrete.

7.5.2 Shell Thickness: Cushions and Indents

Understanding the effects of the cushions: Measuring the cushions and thickness of Shells 1 and 2

The underside of the shell exhibited cushioning effects with noticeable thickness variation. The thickness of the shell was determined by the difference between the upper and undulating under-surfaces of the shell. Seen earlier, the under-surface exhibited cushioning effects resulted from the sagging of fabric under concrete self-weight. Thicker sections of shells were observed in the middle of each diagrid and indentations occurring at where grid laths positions were with the highest layer of gridlaths defining the cushioning most. In addition, a visual inspection showed the regions near the abutments appearing thicker, possibly due to concrete slipping towards the abutments exacerbated by trowelling movements.

This under-surface was marked with indented lines and cushions, clearly marking the gridshell formwork positions. A visual inspection also described two types of indented lines - deeper ones marked by the primary gridmat and shallower lines marked by the stiffening members that braced the gridshell formwork which were at the lowest level.

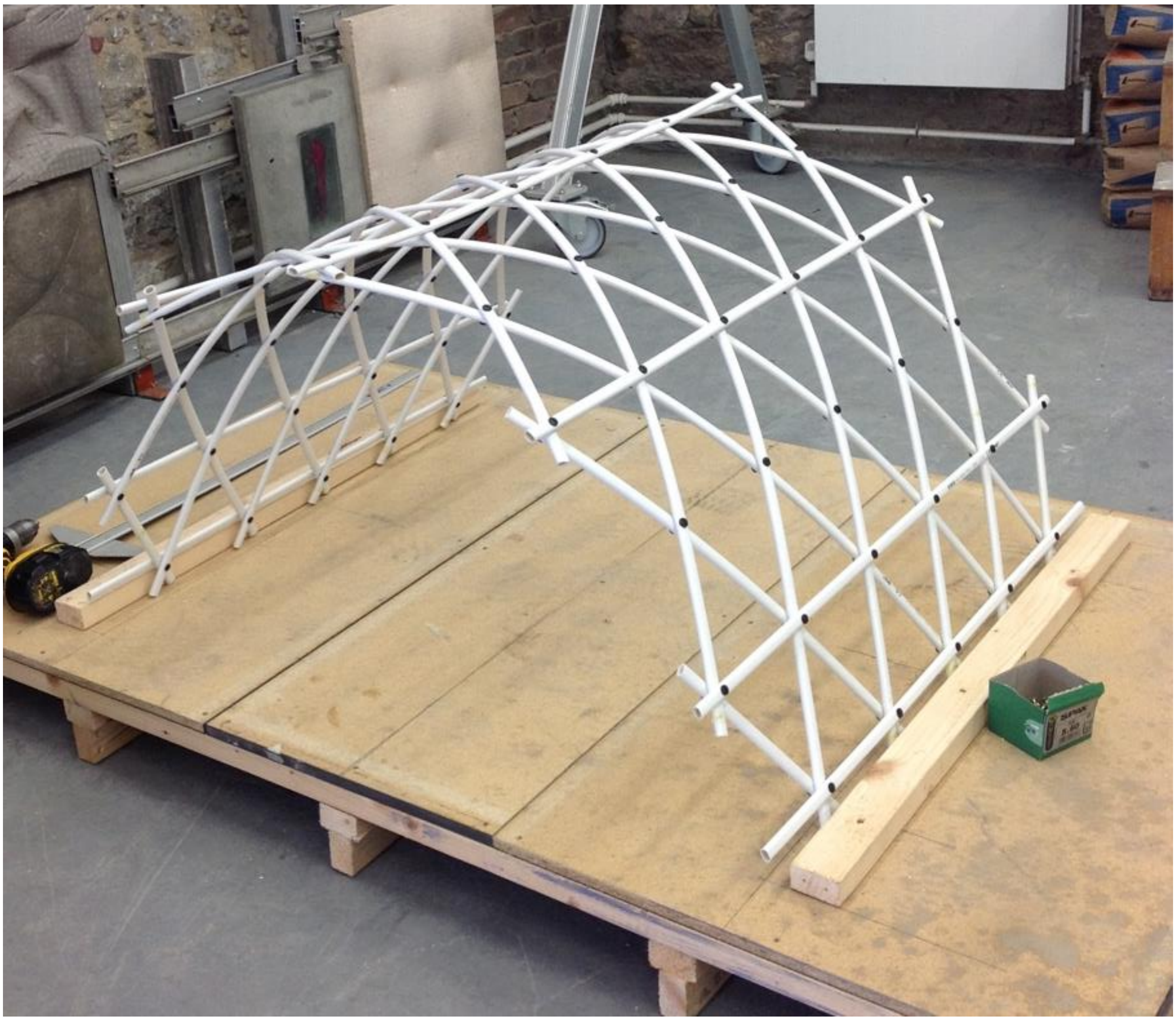


Fig 7.64 The position of each structural member of the gridshell layer changes the way each the shell appears from the underside when the concrete is poured onto the gridshell formwork.

Fig 7.65 The underside of the shells clearly shows the sectioning caused by the patterns of the gridshell

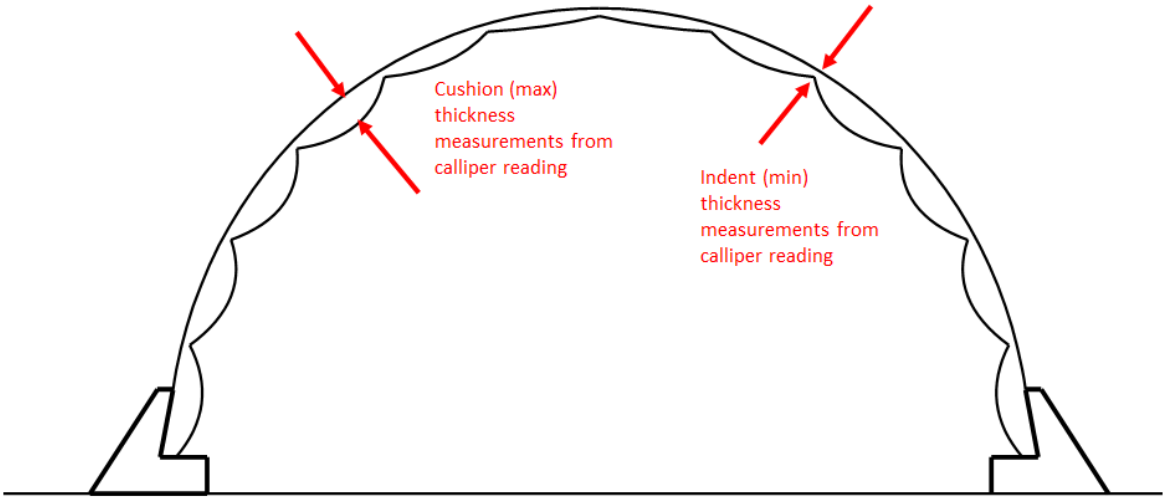


Fig 7.66 The underside of the shells clearly shows the sectioning caused by the patterns of the gridshell

Indentations and Cushions

Whilst measurements taken from the steel frame described geometry of the upper surface, dimensions of the thickness variation of the shell provide an understanding of dimensional change as an effect of concreting process. This result would tell us not only about variation of shell thicknesses but also the degree of indentation and cushioning described by fig 7.65. The deeper dominant lines were made by the primary gridshell members whilst shallower lines were inscribed by stiffening bracing members. This pattern and cushion thickness of the shell will influence structural performance. Without taking measurements, it would not be possible to understand the corrugations, especially how thick are the cushions and how thin at the valleys (or indentations).

7.5.2.1 Measuring procedure

Without scanning equipment to measure shell thickness, an alternative was to measure the thicknesses of the cushions physically. The initial intention was to drill through the thickness of the shell to measure the thicknesses of the shell. Deemed excessively invasive undermining structural integrity of the shell, this idea was abandoned.

A bespoke symmetrical and double-sided calliper was devised and fabricated from laser cutting mild steel. Bolted at the centre, it could reach a distance of 600mm into the shell from the edges adequate for this purpose. With one end of the calliper measuring the thickness at specific positions, the dimension could be transferred to the other end and be read using a micrometre. This procedure required co-ordination of two persons - one measuring and the second, reading and recording the dimension as shown in the figure below. It was difficult to ensure the perpendicular distance is being measured. Due to the weight of the apparatus, it was also difficult to coordinate this.
The measurements are taken point by point moving across the shell.

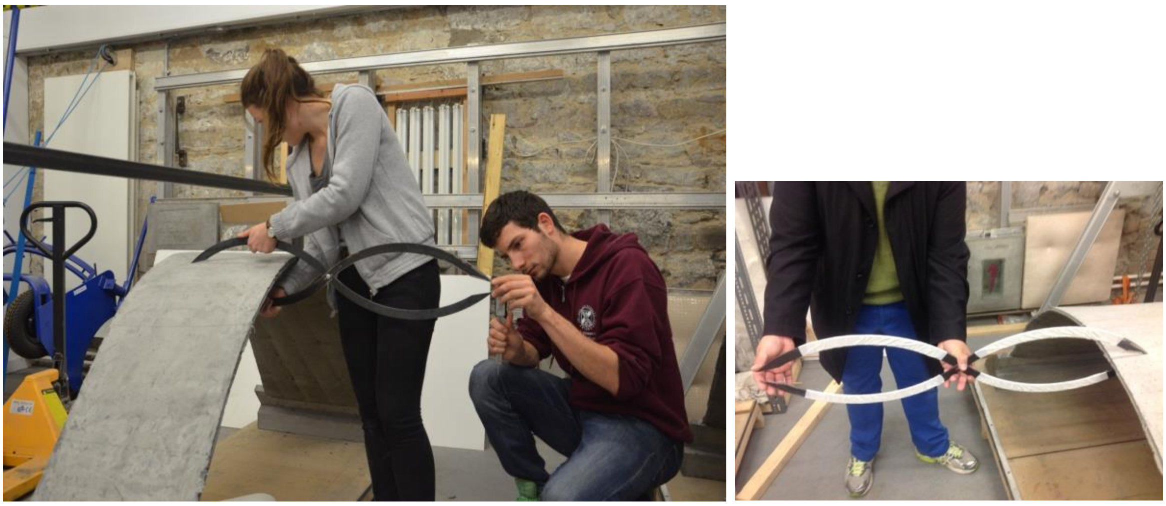


Fig 7.67 The underside of the shells clearly shows the sectioning caused by the patterns of the gridshell (courtesy Dawydzik, 2015)

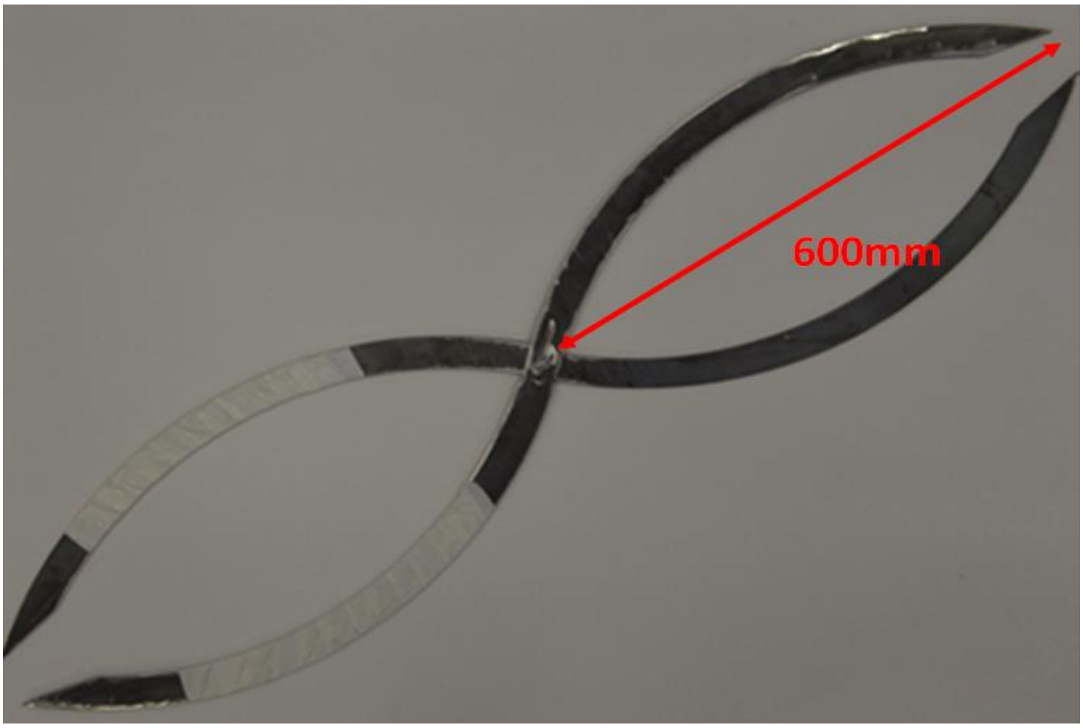


Fig 7.68 Measuring the shell thickness of Shells 1 and 2 using a specially made calliper.

7.5.2.2 Results

The data recorded can be found in appendix B. To make the data more comprehensible and useful, they were input into Excell to extract maximum, maximum and average dimensions at various parts of the shells. The thickest sections of the shell appeared at the areas closest to the abutments highlighting the un-controllability of construction through the large deflections experienced by the gridshell during casting. This could be explained by the tendency for the concrete to slide downwards to the abutments. Shell thickness data were taken from both indent lines and cushions across the span of both shells 1 and 2 and are presented in the charts and graphs below:

Shell 1

Although Shell 1 measured an average of 29mm throughout, the data collected showed how uneven the structure was. The data uncovered large variations between the thinnest and thickest parts of the shell measuring between 9mm and 63mm, representing 7 times of the thinnest dimension with a difference of 54mm. This figure highlights the uncontrollability of the construction process. With a span of 1300mm, this variation represented 4% of the span, indicating the increase for geometry control as an important aspect of improvement. The regions near abutments (first third and final thirds) are thickest measuring between 60mm and 67mm. From fig. 7.72, we see that the first third and the final third both averaged 62mm and 63mm respectively whist the middle third had an average of 41mm.

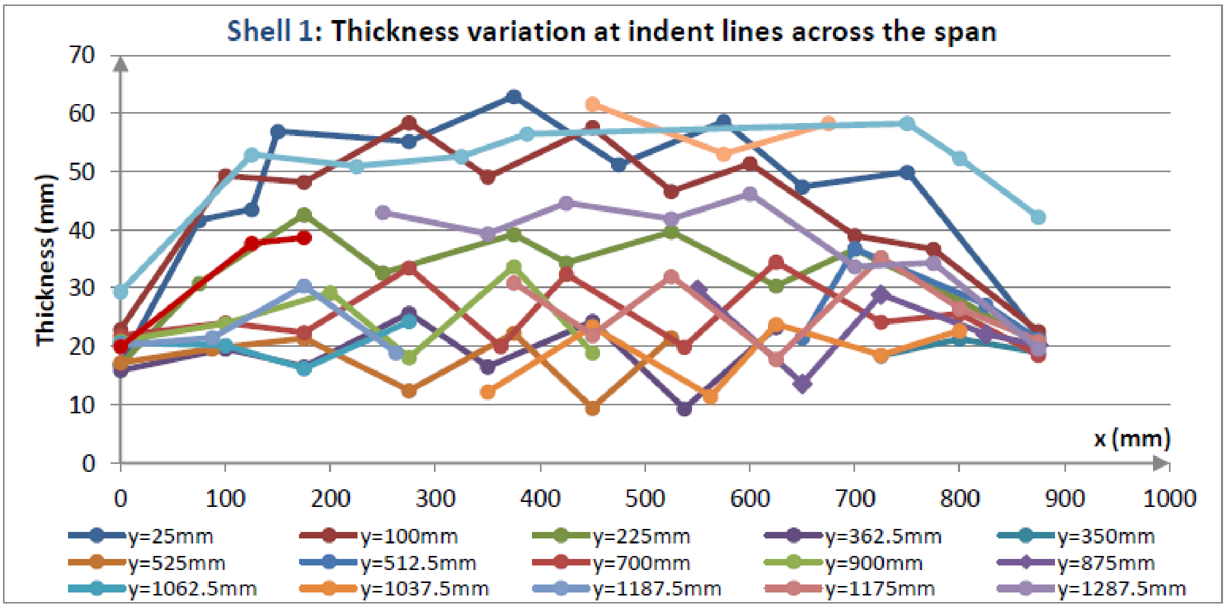


Fig 7.69 Thickness variation at indent lines (thinnest parts) across the span of Shell 1 (courtesy of Walejewska, 2015)

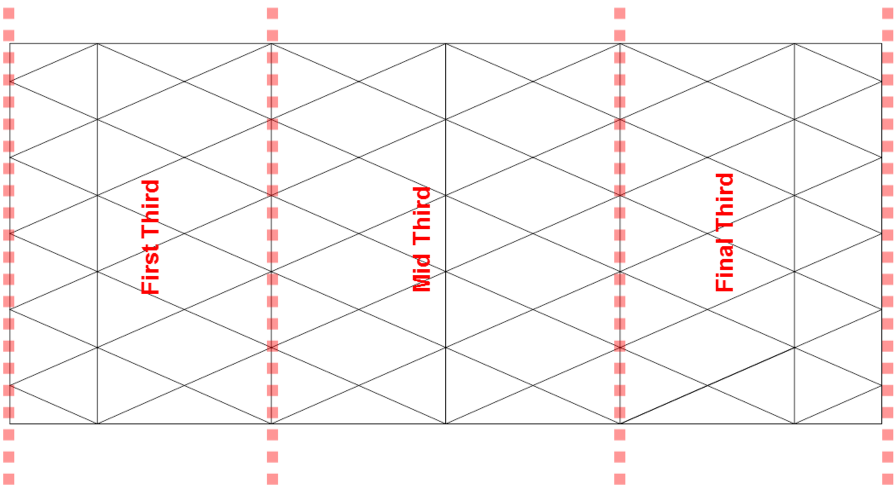


Fig 7.70 Thickness variation at indent lines (thinnest parts) across the span of Shell 1

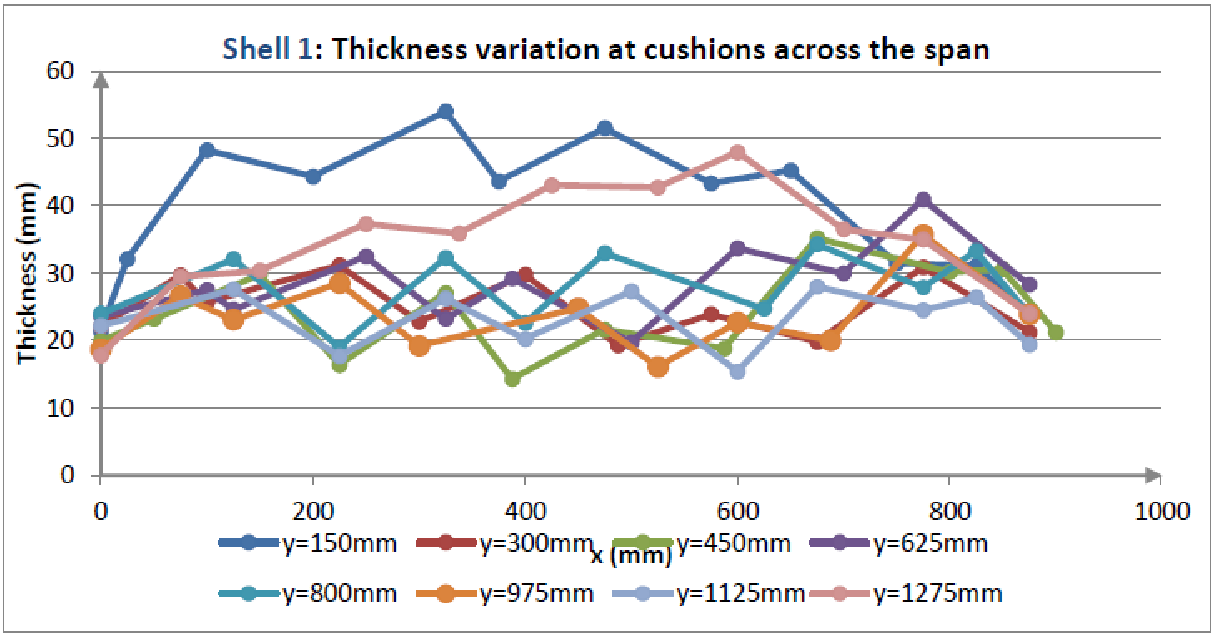


Fig 7.71 Thickness variation of cushions (Thickest parts) across the span of Shell 1 (courtesy of Walejewska, 2015)

section of a shell (mm)	average (mm)	minimum (mm)	maximum (mm)	Section of a shell (comment)
Entire shell	29	9.3	62.9	*entire shell*
Sec. 1 (0-450)	33	9.3	62.9	*first 1/3*
Sec. 2 (450-900)	25	9.4	40.9	*middle 1/3*
Sec. 3 (900-1350)	30	11.4	61.6	*last 1/3*

Fig 7.72 Shell 1: Summary of Thickness variations (courtesy of Walejewska, 2015)

Shell 2

A variation between 11mm at the minimum and 67mm at the maximum was observed i.e. the thickest cushion of more than 6 times between the thickest and thinnest indentation shell thickness with a difference of 56mm, representing a variation to span ratio of 4%. Like shell 1, shell 2 has thickest cushions near the abutments measuring a maximum 67mm and 60mm. The middle section is comparatively thinner (max 40mm).

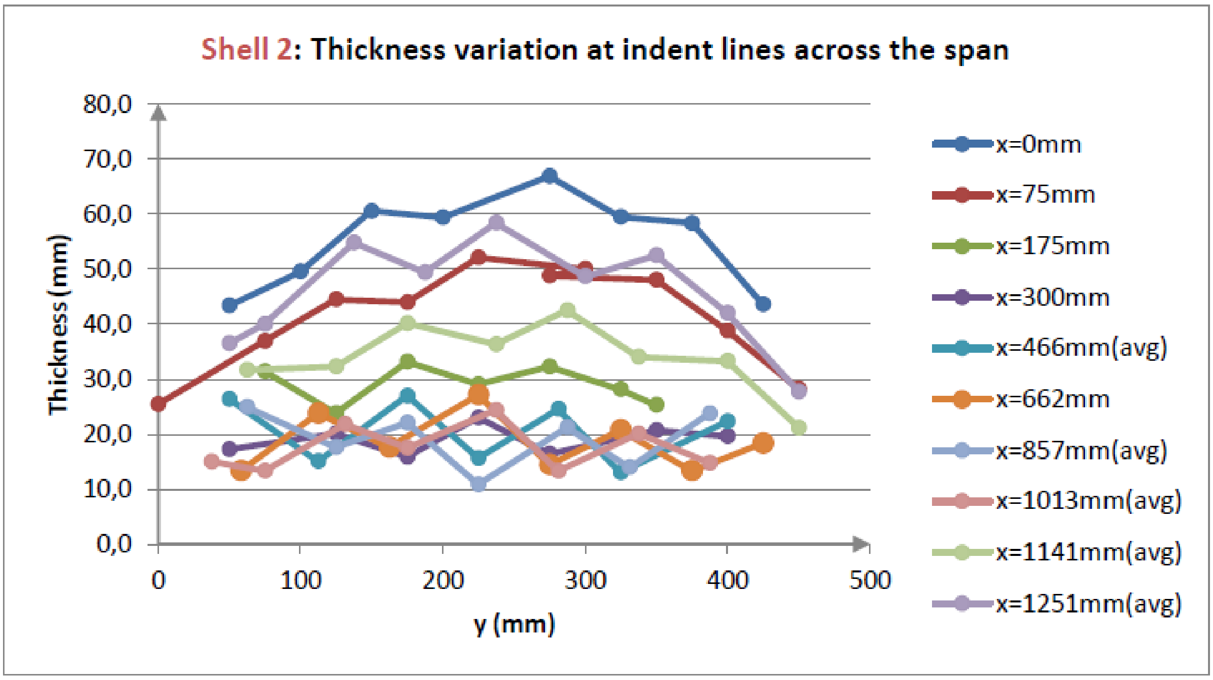


Fig 7.73 Thickness variation at indent lines (thinnest parts) across the span of Shell 2 (courtesy of Walejewska, 2015)

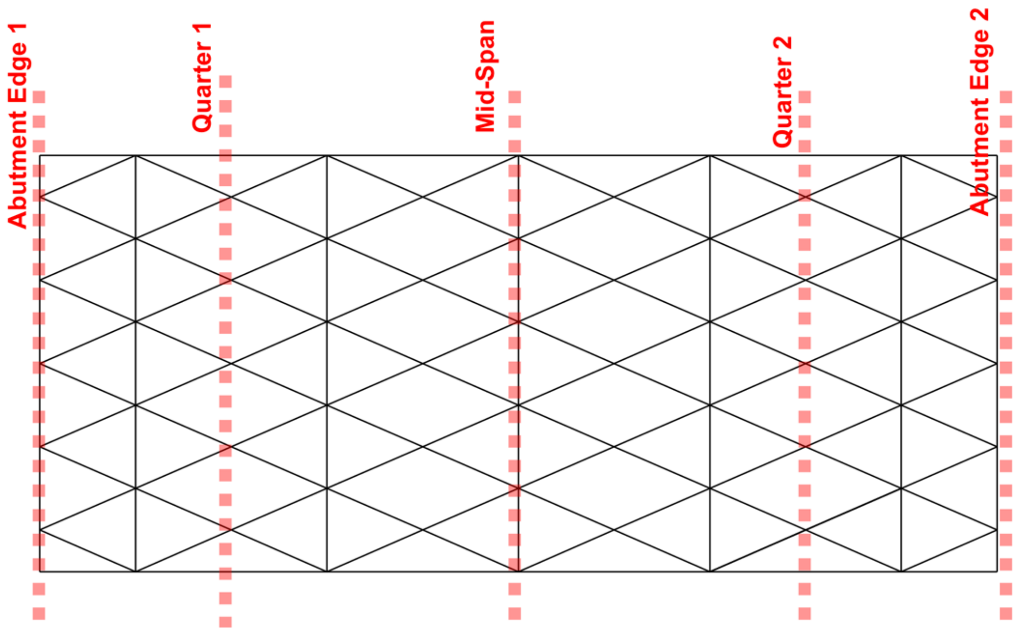


Fig 7.74 Thickness variation at indent lines (thinnest parts) across the span of Shell 1

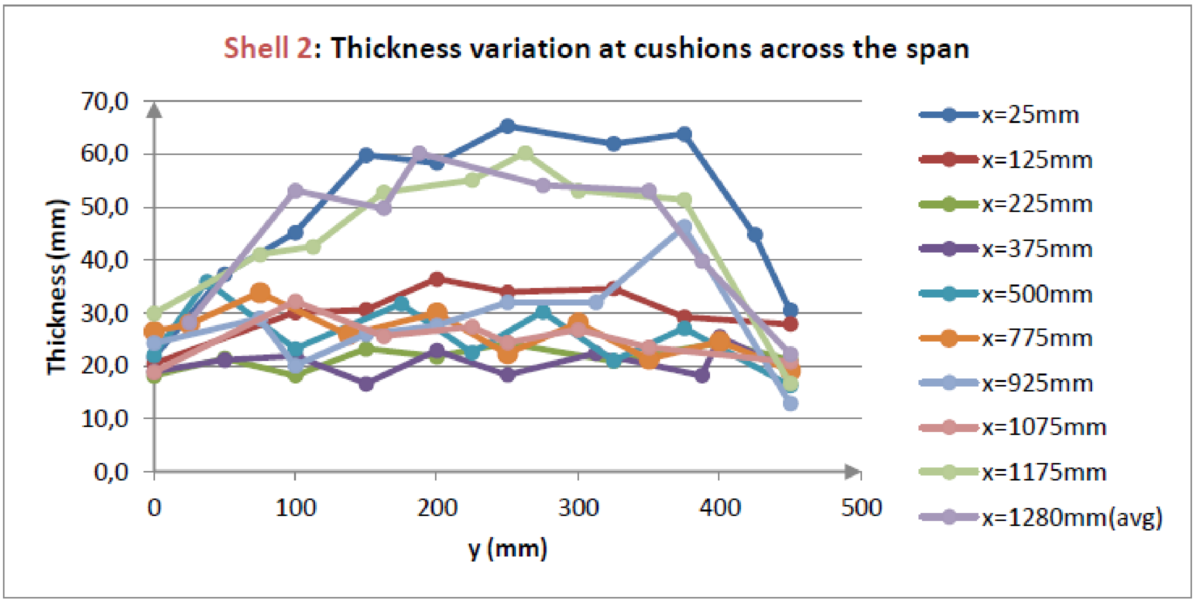


Fig 7.75 Thickness variation of cushions (Thickest parts) across the span of Shell 1 (courtesy of Walejewska, 2015)

section of a shell (mm)	average (mm)	minimum (mm)	maximum (mm)	Section of a shell (comment)
Entire shell	31	11	67	entire shell
Section. 1 (0-425)	34	16	67	*first 1/3*
Section. 2 (425-850)	23	13	36	*middle 1/3*
Section. 3 (850-1300)	33	11	60	*last 1/3*
Sec. 1 (0-100)	48	22	67	*thickest line of cushions near abutment 1*
Sec. 2 (100-1100)	23	11	46	*middle section*
Sec. 3 (1100-1300)	42	17	60	*thickest line of cushions near abutment 2*

Fig 7.76 Shell 2: Summary of Thickness variations (courtesy of Walejewska, 2015)

7.5.2.3 Evaluation and Discussion

Measurement difficulties was experienced which may influence the accuracies of the results.

- With a loosening bolt, the heavy calliper had to be tightened up numerous times during the measuring process. This loosening may have resulted in inaccuracies in measurements.
- The sharp edges of the callipers also meant that to make the process safer, handles had to be taped up with high density tape.
- Due to the geometry of the shell, it was difficult to ascertain perpendicularity (that the callipers were placed at right angle thickness rather than at an oblique angle of the callipers to the shell surface as well. To reduce inaccuracies, the calliper was moved around to find the two dimensionally closest points and thrice repeated with the lowest value noted.

Upon eventual completion of structural testing, various points along the cracks and fractures were cross-checked with data obtained from the callipers. By measuring particular pieces of the broken shell with thickness measurements produced highly similar results with small discrepancies of less than 3mm.

Examining the averages for Shell 1, a symmetrical thickness pattern was exhibited. The shell was thinnest at lines 337.5mm and 1037.5mm at an average thickness of 19.1mm and 19.4mm respectively.

Average thicknesses for Shell 1 (cushions and indentations combined) are schematically presented below:

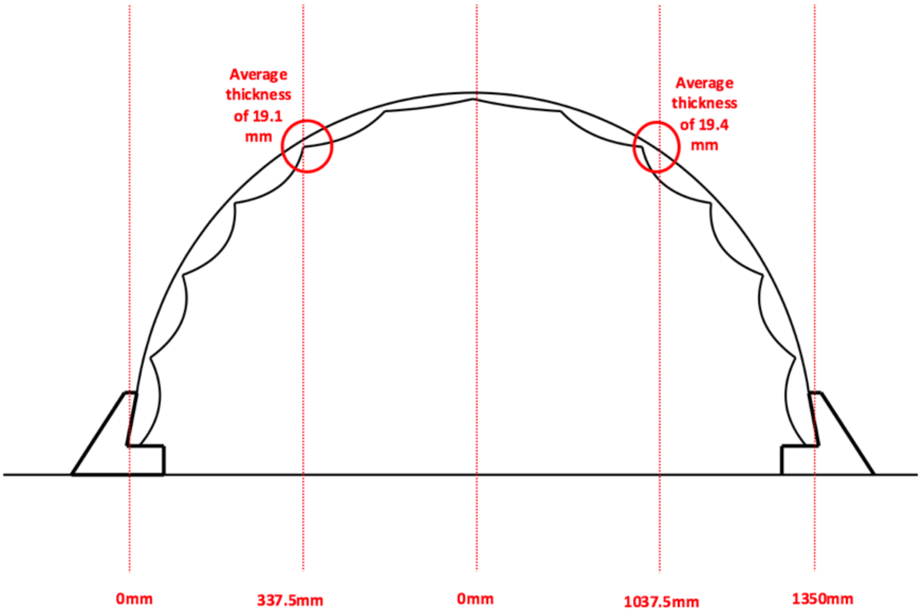


Fig 7.77 Shell 1: Schematic cross section showing average thicknesses (cushions and indents combined) along the span of the shell.

0mm away from right hand free edge	46
75	43.8
200	31.9
337.5	19.1
500	20.9
675	25.2
875	23.6
1037.5 (indent line varying)	19.4
1162.5 (indent line varying)	25.1
1287.5 (indent line varying)	36.3
1350	48.2

Fig 7.78: Detailed average dimensions for effective distances away

At the cushions of shell 1, again, studying the average figures for shell thickness, they measured between 23.2mm and 28.5mm. Atypically, the thicknesses of the cushions at the ends adjacent to the abutments displayed an atypically larger figure at 39.2mm and 34.5mm. The thickest points are at 0mm and 1350mm spans ie at the abutments.

For shell 2: Average thicknesses for Shell 2 (cushions and indentations combined):

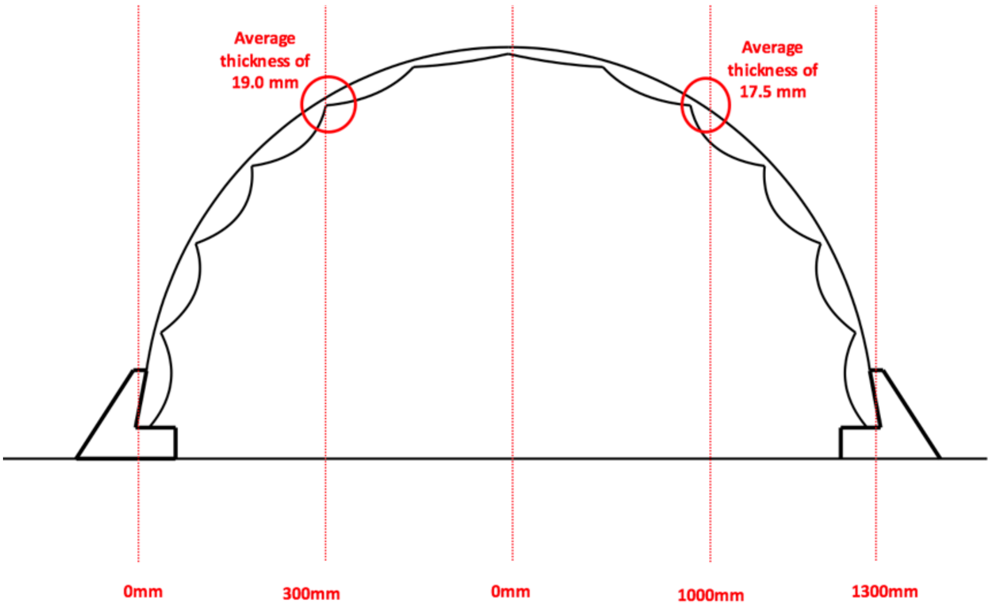


Fig 7.79 Shell 2: Schematic cross section showing average thicknesses (cushions and indents combined).

0	55.1
75	41.7
175	29.0
300	19.0
450 (indent line varying)	20.6
650 (indent line varying)	18.6
850 (indent line varying)	19.2
1000 (indent line varying)	17.5
1125 (indent line varying)	33.9
1238 (indent line varying)	45.6

Fig 7.80: Detailed average dimensions for effective distances away

Looking at the averages for shell 2: an asymmetrical thickness pattern was again exhibited. The shell was thinnest at lines 300mm and 1000 mm at an average thickness of 19.0mm and 17.5mm respectively. Like shell 1, the thickest sections are near the abutments measuring 55.1mm average at 0mm span and 45.6mm average at 1238mm at the other end. These thickness observations coincided with the meeting of concrete between the apex and the lower sections nearer the abutments.

7.5.3 Load Testing

Static load tests were carried out to understand the shell stiffness. The load test was designed to investigate how the physical shell practically reacts to an imposed force.

7.5.3.1 Measuring Procedure

At quarter spans and mid-span, holes were drilled and weights hung at evenly spaced points along mid- and quarter span lines across the shell. Drilling was carried out slowly and carefully to minimise and avoid vibrating and disturbing the structure.

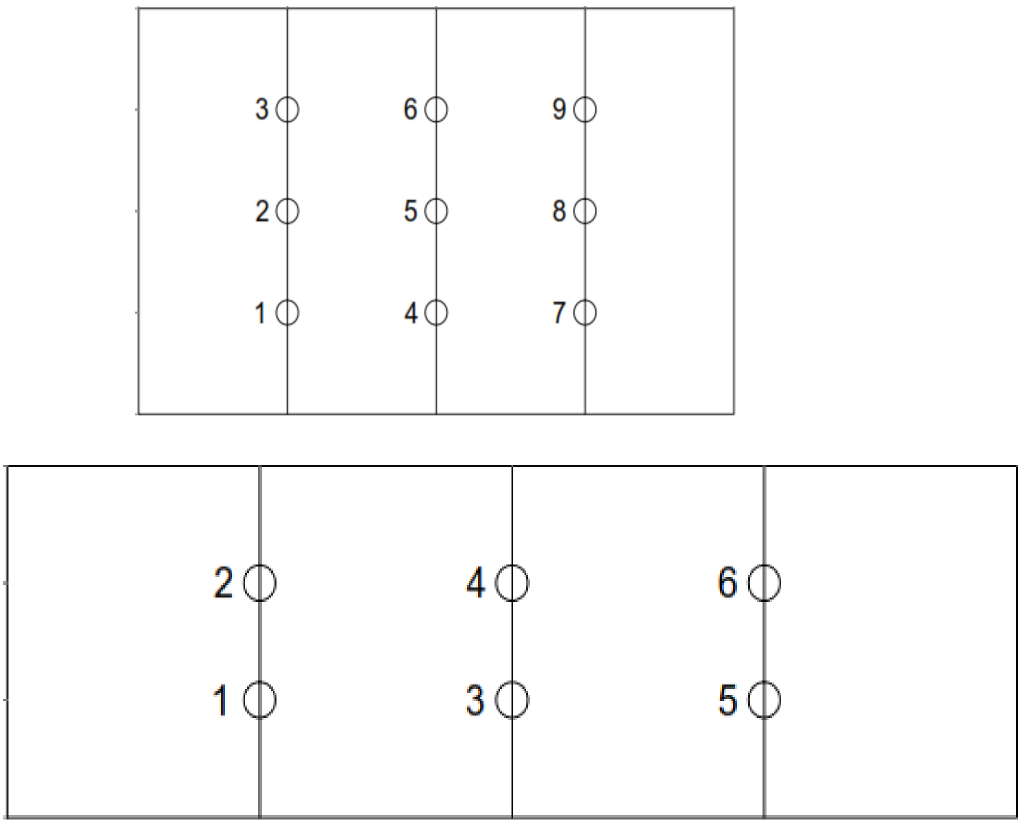


Fig 7.81 Location of gauges' position
(top) Shell 1
(bottom) Shell 2 (courtesy Dawydzig, 2015)

Fig 7.82 Drilling holes for checking (courtesy Dawydzig, 2015)

12 mm thick mdf boards were cut into 40mm square blocks, with 8mm diameter holes drilled through for wires to pass through. Each wire wrapped around a wooden dowel at the top, passing through the same hole and forms a ring at the bottom for weights 10kg, 20kg and others which were placed onto 0.5kg and 1 kg hooks.

Fig 7.83 Holes were drilled into the shells to prepare for loading / deflection tests. Loads were suspended from each line of hooks and deflection was taken

7.5.3.2 Shell Deflection and Displacement at Point

To check for any movements as a result of the loading exercise, displacement gauges were attached to specially welded frames clamped to the bottom of the bases to minimise errors during taking of measurements.

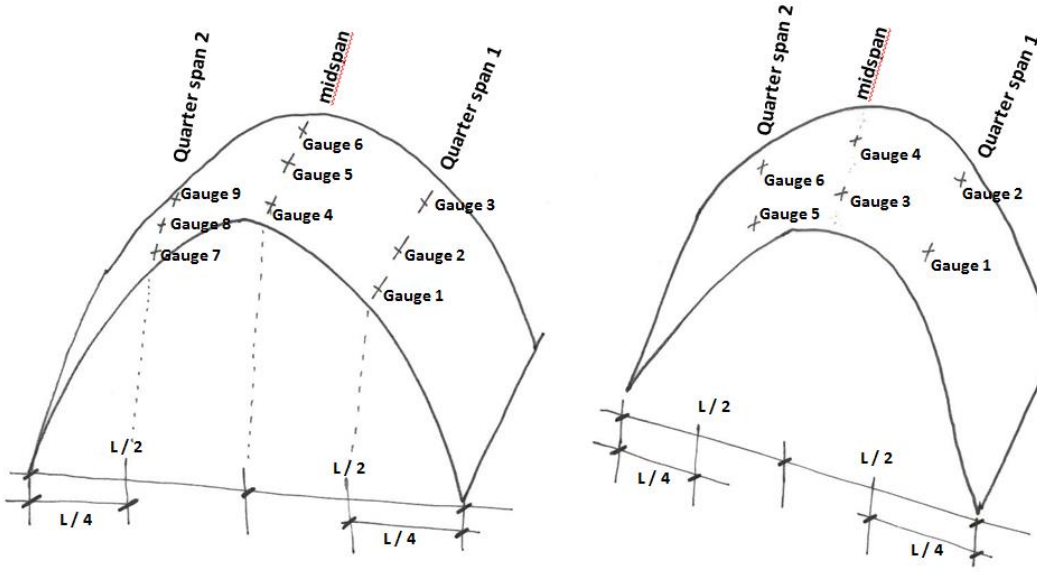


Figure 7.84 explains the location of Q1 and Q2 for Shell 1 (left) and Shell 2 (right).

Loading began with hooks at mid span, first Q2, then Q1 where each position was loaded at 2kg increments. Due to unevenness of the upper surface, beam loading is deemed to produce inaccurate loading scenario and subsequently point loading at the allocated points were used instead.

The exercise recorded total loads of 234kg for shell 1 and 130kg for shell 2 with displacement results presented in the charts below and gauge positioning illustrated in fig. 7.84 above. The loading conditions did not result in structural failure and soon, all available weights were employed to no effect for both cases.

At first, digital gauges were used for Shell 2. Unfortunately, the equipment turned off on their own accord after a few load increments. It was therefore impossible to record the previous measurement before they were turned off. It was decided that measurements had to be repeated without the use of digital gauges. Unfortunately, due to a shortage of deflection gauges, a couple of them still had to be used. Data was taken by turning them on and off before each load increment, resulting in some recordings being unreliable.

Another problem faced was the shortage of weights available for this exercise. Additionally, the handling of 10kg and 20kg weights proved difficult. With having to hang these from the underside of the shells, some weights were dropped several times, causing vibrations that may have yielded inaccuracies of the sensitive measurements, especially when taken in the orders of 0.01mm. Therefore, there may not be sufficient load to detect stiffness.

7.5.3.3 Concrete shell Self-Weight

As the concrete shell was applied onto an actively-bent a flat gridshell, the deadweight of respective shells can be determined with the knowledge of the average thickness of the concrete shell.

Shell 1

Volume of concrete shell:

1.65m x 0.9m x 0.03m = 0.445 m3

weight of concrete shell 1 = 0.445 m3 x 2400kg/m3 = 106.92kg

This covered an area of 1.3m x 0.9m = 1.17 m2

Shell 2

Volume of concrete shell:

1.9m x 0.47m x 0.03m = 0.026m3

weight of concrete shell 2 = 0,026 m3 x 2400kg/m3 = 62.4kg

This covered a floor area of 1.35m x 0.47m = 0.6345 m2.

7.4.3.4 Results

		Displacement (mm)			
	Gauge no	***Midspan loading***	***Quarter 1 loading***	***Quarter 2 loading***	*Total load*
Quarter 1	***1***	-0.72	-0.75	0.04	234kg
	2	-0.44	-0.34	0.03	
	3	0.56	-0.34	-0.04	
Mid-span	***4***	-0.82	-0.54	-0.24	234kg
	5	-0.55	-0.46	-0.36	
	6	-0.67	-0.35	-0.42	
Quarter 2	***7***	-0.22	-0.05	-0.30	234kg
	8	-0.20	0.00	-0.45	
	9	-0.32	0.05	-0.75	

Figure 7.85 Shell 1: Summary of Displacements for total load of 234kg (courtesy of Walejewska, 2015)

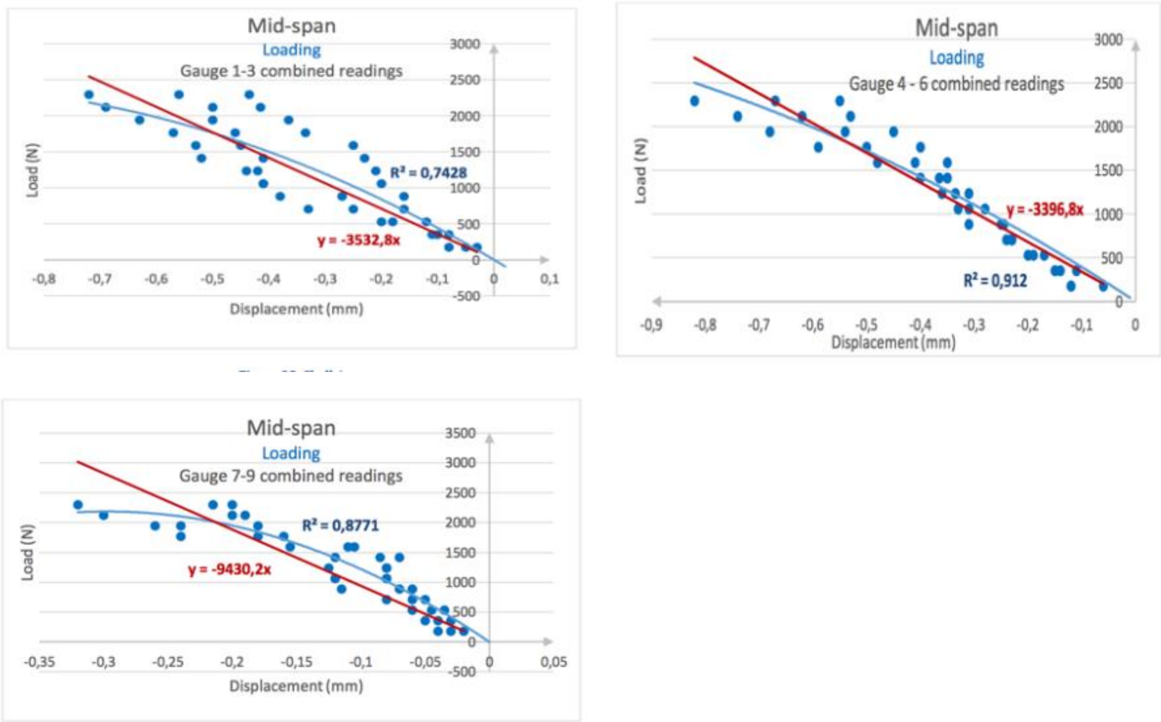


Fig 7.86 Displacement/ Loading data for Shell 1 (courtesy of Walejewska, 2015)

Shell 2

		Displacement (mm)			
	Gauge no	***Midspan loading***	***Quarter 1 loading***	***Quarter 2 loading***	*Total load*
Quarter 1	***1***	-0.27	-0.66	0.02	130kg
	2	-0.15	-0.35	-0.03	
Mid-span	***3***	-0.48	-0.25	-0.23	125kg
	4	-0.44	-0.04	-0.12	
Quarter 2	***5***	-0.40	0.24	-1.44	130kg
	6		0.51	-1.08	

Fig. 7.87 Summary of Displacements for total load of 125 kg – 130kg in Shell 2 (courtesy of Walejewska, 2015)

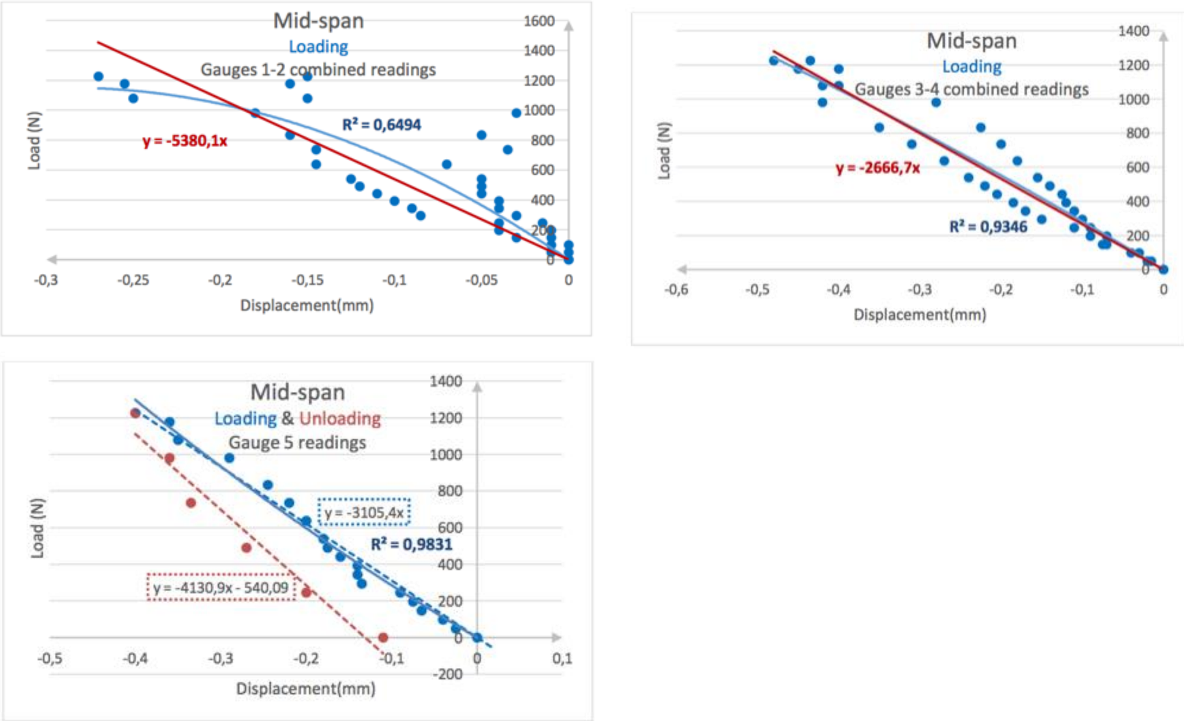


Fig 7.88 Displacement/ Loading data for Shell 2 (courtesy of Walejewska, 2015)

7.5.3.5 Discussion

With the limited amount of load available, the data displayed a linear load to displacement relationship implying constant stiffness and plastic shell behaviour with small movements. The measurements for Shell 1 ranged from -0.82mm to 0.56mm, representing a variation of 1.38mm which equated to 0.1% of shell span. For Shell 2, deflection ranged from -1.44mm to +0.51mm representing a deflection range of 1.96mm (0.145% of shell span).

To represent data obtained, the data was imported into Microsoft Excel and deflection vs load graphs were plotted for each gauge meter and the average line drawn of displacement versus load to suggest a linear relationship, i.e. an elastic response. The results for mid- span and quarter- span loadings are presented for Shells 1 and 2 below. This is very small and in order to induce larger deflections, it was decided that hydraulic jack testing is carried out on the concrete shells instead.

In this test, it is apparent that for shell 1 weighing 106.92kg, was able to withstand 234kg (219% of self weight) in linear loading experiencing deflections of 1.38mm (0.1% of shell span).
For shell 2 that weighed 62.4kg, it was able to withstand at least 130kg linear loading (208% of self-weight) with recorded deflections measuring 1.96mm (0.145% of shell span).

7.5.4 Failure Testing

7.5.4.1 Test set up and measuring procedure

To perform this, a hydraulic jack was fixed under an I-beam and the shell lifted and manoeuvred to align shell centre with the hydraulic device. Load spreaders were custom-made to distribute load between four equally spaced points described in figure 7.89 and fixed mid-span. The load spreader sat on 40mm squares mdf pads attached to the top of the shell with plaster to spread the loads. This is not ideal for the geometry of the shells but for convenience of analysis, the apparatus was set up this way.

Fig. 7.89 Loadspreaders on shell

7.5.4.2 Results

The same steel frames specially welded for static load testing were positioned at quarter spans with 2 gauges secured at each of them. Loading was applied slowly in 0.5kN increments and displacements were recorded at each increment. This was carried out until the shell reached failure.

Shell 2 was tested first. After load failure of Shell 2 was reached, load increments were reduced to 0.2kN increments. As well, to record and study this displacement, two cameras were set up either side of the shell to record the displacement.

Fig 7.90 Failure Test underway

A crack was observed before the start of the experiment at quarter span Q2 of shell 1 which may have influenced failure behaviour. This may be attributed to forklifting, moving and re-positioning the shell. The crack was repaired by gluing epoxy glues to adhere it together.

Fig 7.91 Crack on shell 1 prior to test

Shell 1

Four deflection gauges were positioned on the shell. 2 at quarter span 1 and the other 2 at quarter span 2. This was set up to further record deflections whilst load was applied at the apex. All the recordings showed the shell moving downwards with downward deflection of the upper surface to 1.11mm before the shell cracked up and collapsed. These measurements were taken within the elastic range. When the first crack was observed indicating failure setting in, the gauges and steel frames were removed and the behaviour of collapse observed in the series of photos presented here. The data, charts and diagram illustrates the findings of this exercise.

	Mid-span loading				
Total load in kg	Total Load (kN)	Displacement (mm)			
		Quarter 2		*Quarter 1*	
		Gauge 1	*Gauge 2*	*Gauge 3*	*Gauge 4*
0	0.0	0.00	0.00	0.00	0.00
51	0.5	-0.22	-0.19	-0.19	-0.27
102	1.0	-0.34	-0.32	-0.33	-0.45
153	1.5	-0.44	-0.43	-0.45	-0.57
204	2.0	-0.55	-0.55	-0.56	-0.68
255	2.5	-0.64	-0.65	-0.66	-0.79
275	2.7	-0.68	-0.69	-0.70	-0.84
306	3.0	-0.73	-0.75	-0.77	-0.91
336	3.3	-0.78	-0.80	-0.83	-0.97
357	3.5	-0.81	-0.84	-0.86	-1.01
377	3.7	-0.84	-0.87	-0.90	-1.05
408	4.0	-0.86	-0.90	-0.97	-1.11
428	4.2	-0.60	-0.54		
357	3.5				

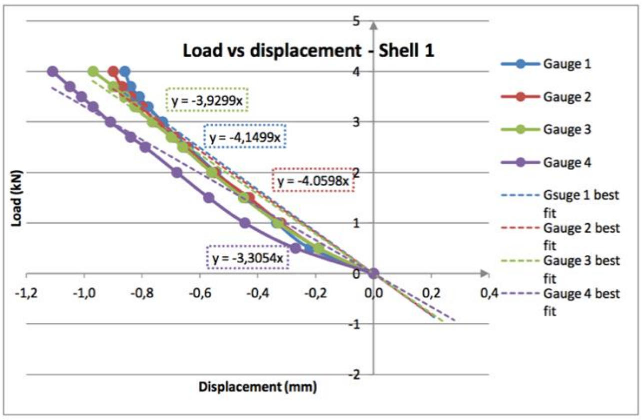


fig 7.92 Failure Data for Shell 1 Load displacement curves including displacements beyond collapse load

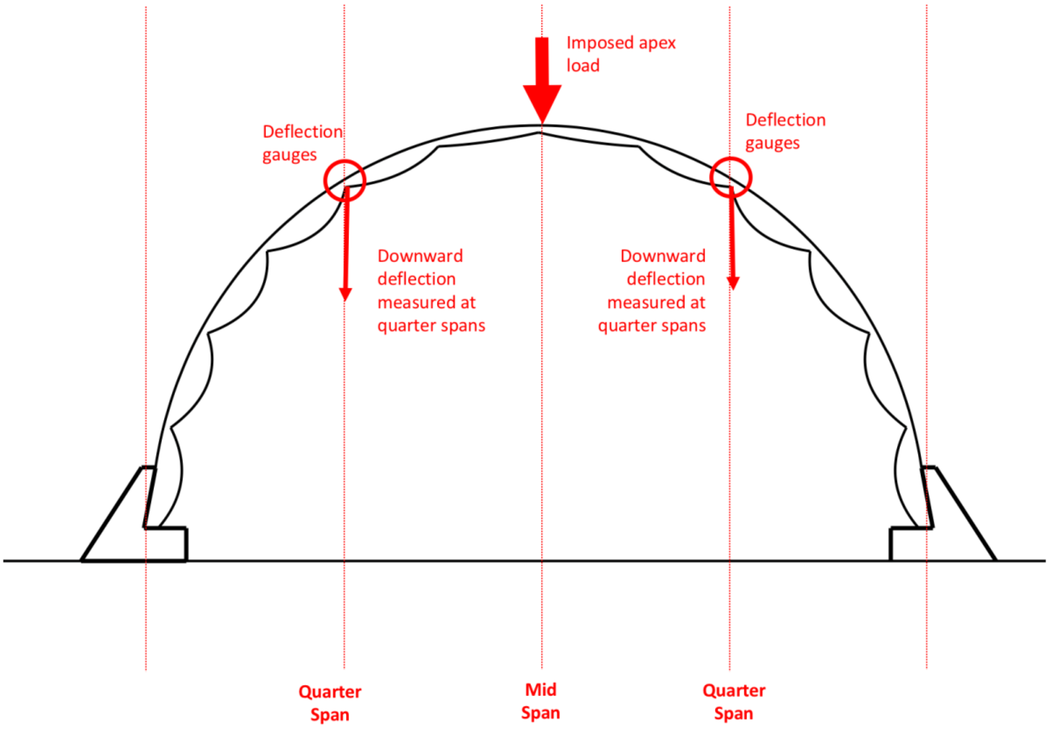


fig 7.93 Failure Data for Shell 1 Load displacement curves including displacements beyond collapse load

Collapse Stills of Shell 1

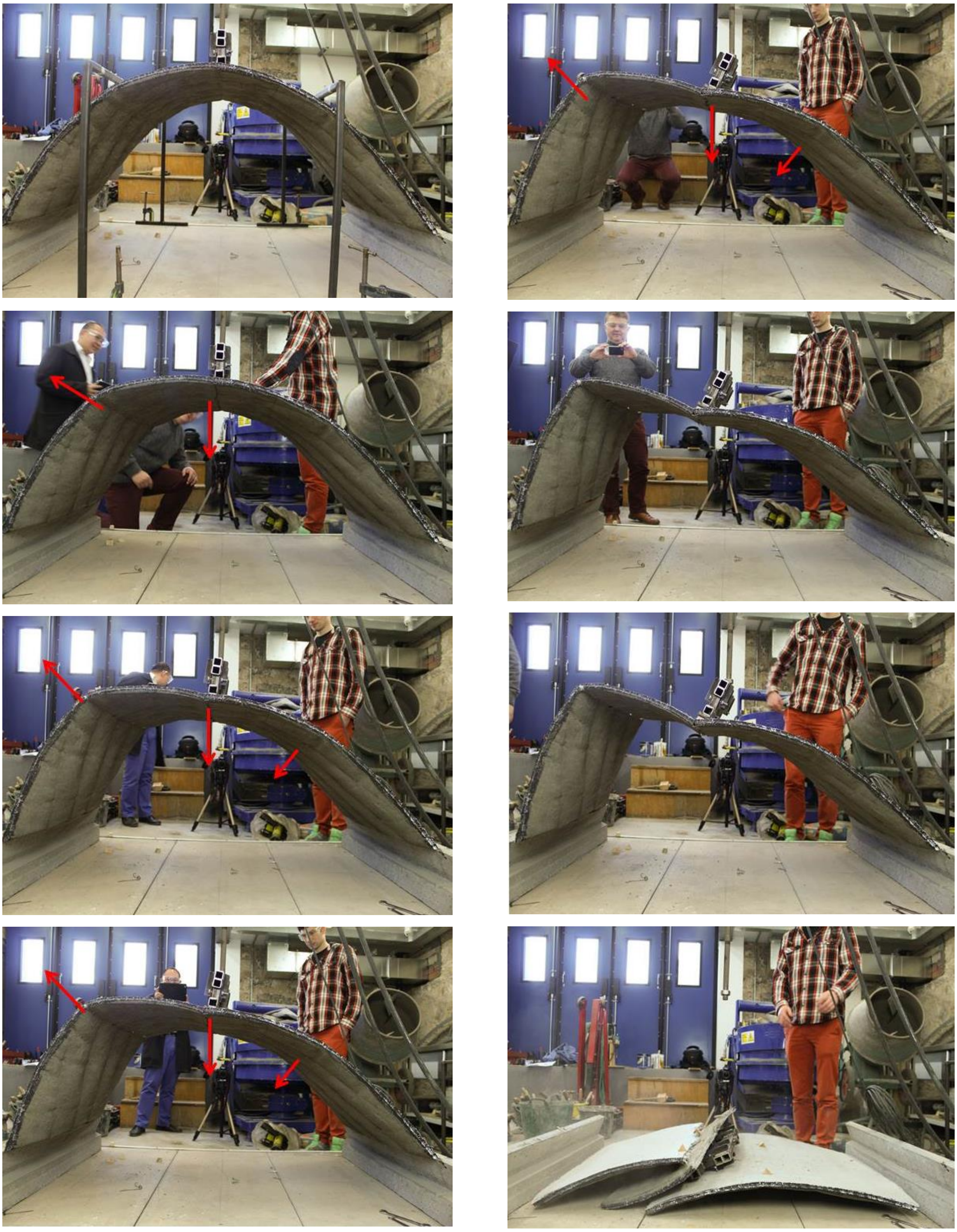


Fig 7.94 When the first major crack appeared at mid-span, the steel frames were removed to prevent hindering the collapse process. As Q2 started moving upwards and Q1 downwards - the entire shell leant towards Q2. It is noted that the shell continued to stand precariously as sections experienced slow ductile plastic collapse due to plastic reinforcements mixed into the concrete.

Shell 2

Four gauges were positioned on the shell for the failure test. Two at quarter span 1 and the other two at quarter span 2 (fig 7.89). The data collected showed the shell deflected downwards at both gauges for Quarter 1 but one of the two gauges, the shell gauge 2 moved upward consistently until 1.31mm before collapse. For gauge 1, this position moved upwards to 2.75mm before it collapsed. Again, gauges and frames were removed when the first sound of cracking was heard and seen. Photos of a time lapse video presented here records the collapse behaviour.

	Mid-span loading				
Total load in kg	Total Load (kN)	Displacement			
		Quarter 2		Quarter 1	
		Gauge 1	Gauge 2	Gauge 3	Gauge 4
0	0.0	0.00	0.00	0.00	0.00
51	0.5	-0.08	0.07	-0,22	-0,16
102	1.0	-0.11	0.06	-0,25	-0,15
153	1.5	-0.11	0.08	-0,24	-0,11
204	2.0	-0.11	0.11	-0,23	-0,07
255	2.5	-0.12	0.14	-0,22	-0,04
275	2.7	2.75	1.31	-0,71	-0,70
163	1.6				

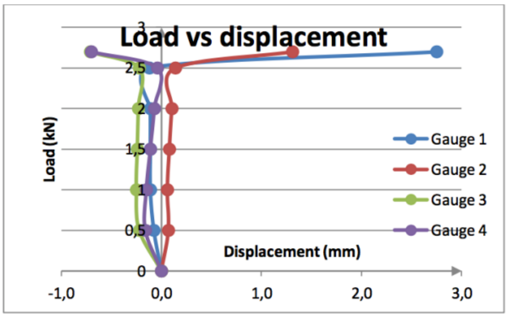


fig 7.95 Failure Data for Shell 2 Load displacement curves including displacements beyond collapse load

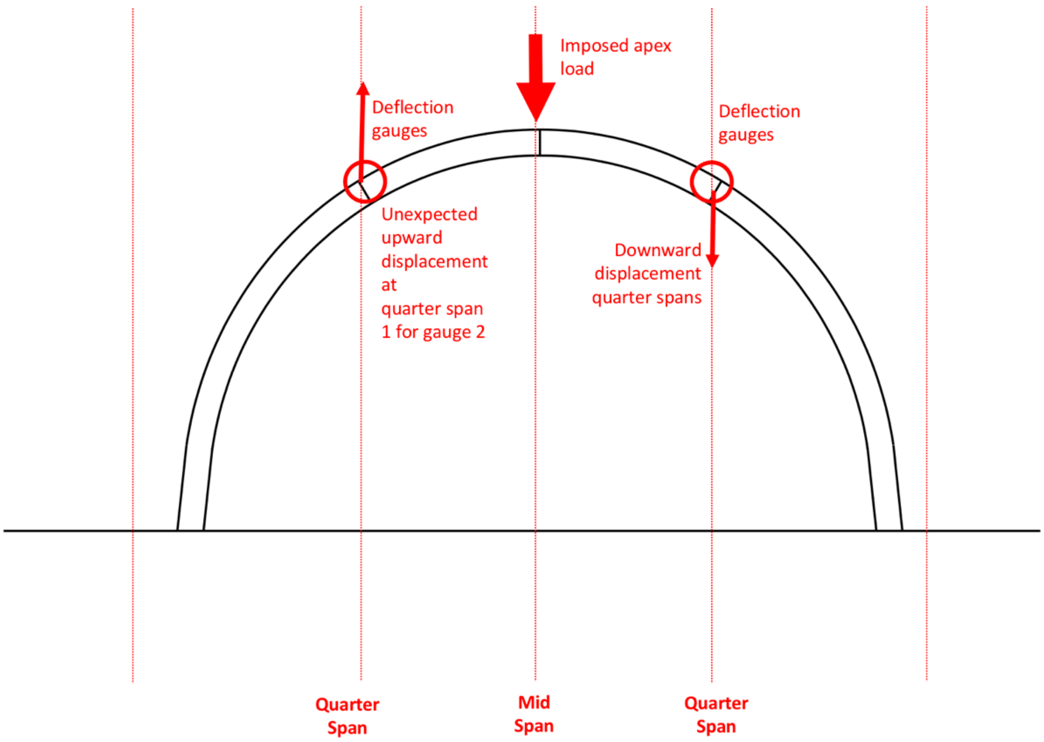


fig 7.96 Failure Data for Shell 2 Load displacement curves including displacements beyond collapse load:

Shell 2

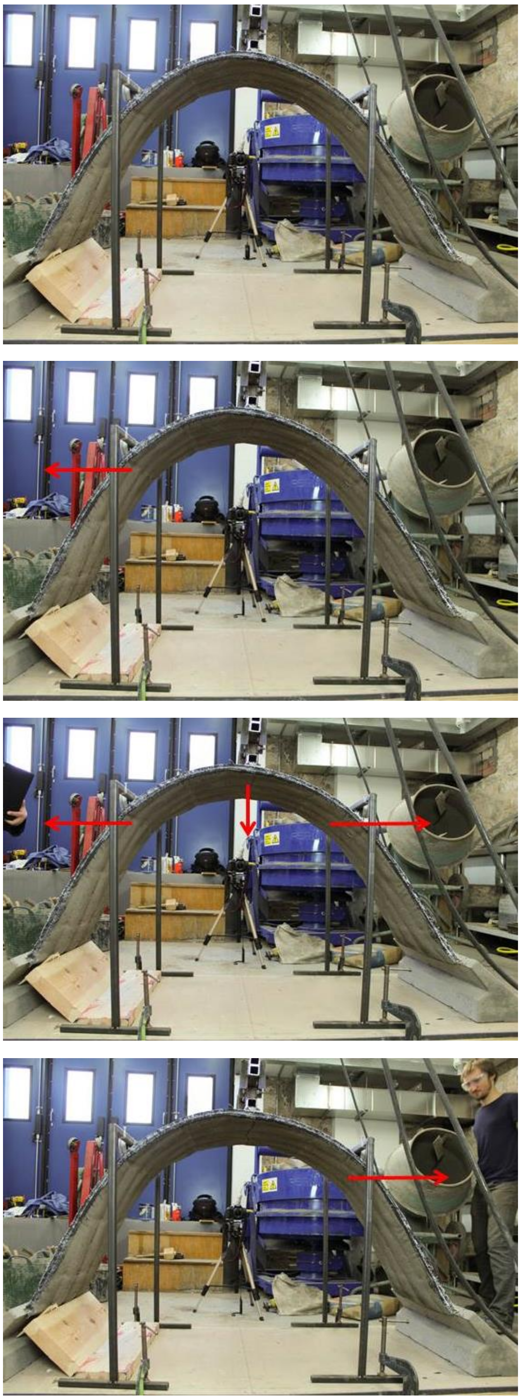


fig 7.97 Failure movement and sequence for Shell 2 Shell 2 exhibited similar reactions during testing. At first, Q1 and Q2 started going sideways then downwards. Following that, cracks appeared at the underside of the structure at mid-span which seemed to have prevented Q2 from moving as Q1 moved upwards. A crack developed at Q2 and caused the structure to reverse the pattern of movement again with Q2 moving upwards whilst the mid span and Q1 downwards, moving to complete collapse

7.5.4.3 Evaluation and Discussion

Fig 7.98 Test Shells 1 and Test Shell 2 in comparison

Shell 1

- Initially, a hairline crack was observed on the underside at mid-span during loading. It continued to take loads until a crack developed at the underside of quarter spans. The shell eventually failed and folded sideways. The side which collapsed first was identified to be the side which has less double curvature on the top, suggesting that top surface flatness is a weakness of a shell.

Shell 2

- A first crack appeared on the upper side of the quarter span, a second crack appeared on the opposite side as well. The shell deflected upwards at both quarter spans before it folded to one side.

- Digital gauges could have resulted in erroneous readings as they switched themselves off when they were kept on for too long, resulting in lost readings when they were switched back on. As such, Shell 1 quarter 1 loading for gauges 8 and 9 had to be repeated. Following this, the use of digital gauges was minimised and used only in areas where displacements are not expected to be too large.

- Due to the shortage of weights which resulted in the substitution of weights by exchanging smaller weights for a single 10kg weight was necessary. During the data recording period, the gauges had to be switched on and off repeatedly.

- It was also noted that access to the underside of the shell was challenging with heavy weights dropping a few times, causing vibrations which may have affected the already sensitive readings. All these factors may have had an adverse influence on the data recorded.

- The trial has shown that it is possible to build concrete shells using deployable and actively bent gridshells.

- Some issues had to be investigated prior to actual construction. Specifically, these relate to the development of double curvature from a flat mat.

- The gridshell deflected considerably whilst concrete was applied on the first and second coat. It demonstrated how uncontrollable this method of construction is.

- During construction, the application of concrete at the sides had compressed the formwork causing it to rise upwards in the middle. When concrete was applied at the apex, the gridshell deflected downwards. Whilst it descended in the apex regions, the shell appeared to have twisted on plan as well. Forces applied during casting process could be transferred to other parts of the shell and cause dimensional changes.

- Both shells failed initially at quarter span zones with the thinnest concrete thicknesses recorded. When examined during the collapse, the shells did develop the initial cracks along the indentations i.e. the deepest lines indicated by the gridshell pattern. This therefore suggests that the weakest points in the shell are not just determined by the shape, geometry or cushion thickness but indentations inscribed on the shell is also a determining factor.

- Other factors may have influenced failure behaviour. At test start, it was observed that the shell may have slipped away from the abutments. A small hairline gap was detected at the abutment at both shells, suggesting a pre-test separation of shell from the anchoring abutment. The concrete shell was effectively not connected to the concrete abutments at the beginning of the experiment. On hindsight, re-bars to the abutments that connected the shell to the precast abutments may have prevented this from happening.

- Another possible influence may have been the movement of the timber base upon which the shell sat may have deflect downwards itself when mid-span load was imposed.

- The critical collapse load was measured to be 4.2kN i.e. 420kg for Shell 1 which is very high failure loading for a shell 1 (106.92kg) representing a collapse load to self-weight ratio of 393%. Beyond that, the shell collapsed completely.

- The critical collapse load for Shell 2 was recorded at 2.7kN (270 kg) for Shell 2 (62.4kg) which is also high representing a collapse load to self-weight ratio of 432%.

- No brittleness was experienced. Ductility and slight plasticity experienced in the concrete shell failure collapse was due to the addition of strux plastic fibres in concrete mix itself. In both cases, the collapse was plastic with concrete held together with strux to bring about plastic behaviour of falling. Through the fissures, the plastic strux could be seen to be holding the various sections of the concrete shell together. The strux fibres only became effective post-cracking and then held the shell together. Without the strux elements in the concrete, the concrete shell would have collapsed much sooner than what was observed. In fact, for both shells, although failure mode was reached, to initiate the collapse, additional forces had to be added on the hydraulic jacks.

- Both of these results evidenced the strength and efficiencies of concrete shells built using gridshells.

7.6 Discussion

7.6.1 Shell Shape

This experiment dealt with the construction of simple symmetrical shells. The shells were straightforward to build. The development of a more sophisticated system of gridshell construction should be investigated with the possibilities of asymmetries and other shell geometries (such as synclasticities and anticlasticities). The structural properties of gridshell and the resultant concrete shell need be tested and investigated.

7.6.2 Edges

The test also demonstrated the importance of the edges. It was designed using the same material as the gridshell to allow a consistency of tectonic language to be expressed within the resultant concrete shell. The consideration and design of the edges can alter the appearance of the concrete shell and deserve design attention, aesthetically to showcase shell thinness which is one of the key features of concrete shells. The photos below show other methods of forming shell edges by Felix Candela during the construction of the saddle-shaped Chapel Lomas de Cuernavaca, Mexico 1958 rising to a height of 21m. The shell was mostly 4cm thick (1 ½ inch) (Garlock and Billington, 2008) but because of the forces at the edges where the shell is connected to the anchor, in response to large stresses, the walls were thickened. The photos show the use of timber boarding positioned upright as a casting stop to produce a sharp shell edge.

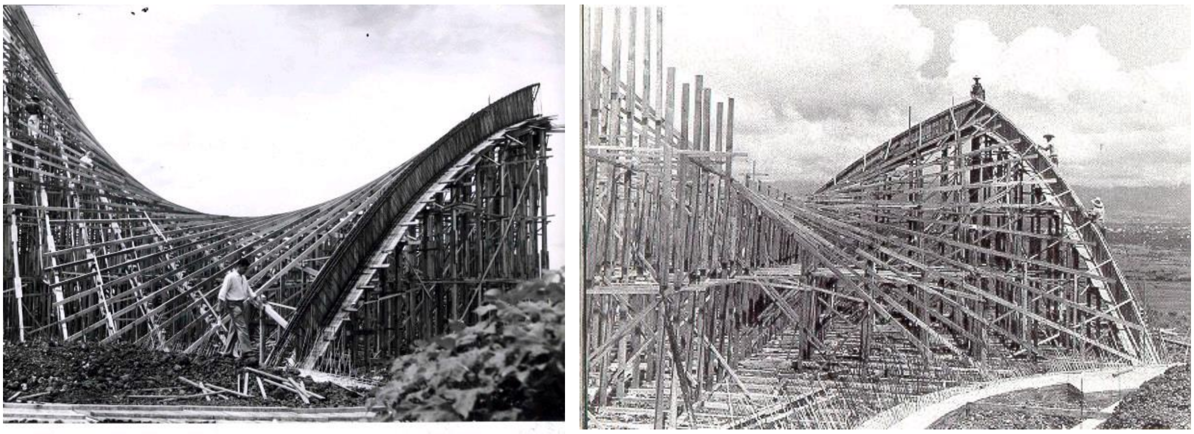


Fig 7.99 Chapel Lomas de Cuernavaca, Mexico (1960)

7.6.3 Scale and Joining Details for extending gridmats

The limitations of this experimental construction lie on the size. 3m lengths of plastic conduits were used. A system to create a continuous surface with a more sophisticated method of material connection and process that addressed a bigger mat with a wider span needs to be explored.

7.6.4 Openings

Openings in surface structure are a key structural aspect of investigation as holes in the structure would weaken it.

7.5.5 Construction Speed

The construction experiment affirms and verifies the hypothesis of shell making using the same deployable gridshell as re-usable formwork. The advantages of this arrangement rely on its reusability and intuitive nature as it self-adjusts to form an shell shape when forces are applied. An intuitive system allows the designer to design and construct freely, without being excessively-limited with force-calculations, therefore reduces the overall construction speed.

This system is seemingly less time-consuming compared to other methods of concrete shell making such as the use of timber planks or even the use of laser cutting machines. In this instance, two concrete shells of different widths and heights were cast from the same gridshell formwork. It is not unimaginable that numerous shells of various dimensions and shapes can be achieved with this system. Compared to earlier methods of working concrete using fabric formwork and other thin shells, this was a much easier and quicker way of constructing concrete shells - a strong sentiment expressed by technicians at Edinburgh University ESALA workshop who had extensive supervision experience.

7.6.6 Material

The shell is limited in formal expression by gridshell material. Although pvc conduits, unlike timber, do not degrade under moisture i.e. left in the rain outdoors; over time, it disintegrates under ultra-violet radiation. An appropriate improvement would be an alternative gridshell formwork material and/ or method. Materially, this idea is cost effective and technically assessable. It is intuitive and made use of easily sourced material. Commonly available and mass-produced machine-made components (binding screws and electrical conduit pipes) could be used in an unexpected way and in unintended scenarios. Lightweight plastic flat head screws designed for book binding were used here as they prevented fabric snagging. Pvc conduits tubes normally used for electric cabling were sourced for their low cost, workability ease and ready availability. Its low-tech nature aligns with the spirit of being resourceful, the very spirit that drove Luigi Nervi in innovating for economy in a material hungry environment.

7.7 Conclusion

This chapter addressed aims set out at the beginning of the chapter.

Firstly, it has evidenced the re-deployability of grid shell by the successful building of two concrete shells of single curvatures from 1 single set of gridshell formwork with fabric covering at relatively small scale. Constructionally, the shells took little time to construct and used little materials. Performance-wise, the gridshell was easy and quick to re-used and reconfigurable to produce shells of different height and dimensions. Structurally, very strong shells were made.

Studies were conducted through the recording of construction process with attention paid to deformation/ deflection of the gridshell formwork during casting (up to the order of 1% rise to span ration in Test Shell 1). This test highlighted the need to curb/control movements during casting.

Clearly, the tests verified the reusability and reconfigurability of gridshell formwork. The resultant concrete shells were elastic when subjected to loading as it exhibited small deflections within elastic range loading. Importantly, this chapter explored the tectonic implications of undulating concrete cushioning although further investigations into the effects of insulation as well as waterproofing should be investigated in greater detail.

At this scale of prototyping, the feasibility of this hypothesis has been proven. Deployable gridshells can be used in the construction of concrete shells. The advantages of this method of construction are its re-usability, re-configurability and ease of use. A scaled-down model here also helped the designer understand and communicate the structure intuitively during the design and construction process.

The following chapter investigates the use of metal gridshell as an alternative to pvc tubes in gridshell formwork. Another idea is to explore opportunities of generating complex double curvatures in the gridshell and subsequently, concrete shell.

Metal Gridshell Formwork, University of Edinburgh, 2015 (Gabriel Tang)

PART 3 CONSTRUCTION AND TESTING

Chapter 8

MATERIAL INVESTIGATIONS AND GEOMETRY IMPROVEMENT

Chapter 8
Material Investigations and Geometry Improvement:
Designing and constructing Shell 3

8.1 Aims: From single to double curvatures using alternative materials

The experimental build and analysis of Shells 1 and 2 in Chapter 7 highlighted the importance of geometry and their influence on shell stiffness of the concrete shell. Prior to the construction of Test Shell 3, the effects of dynamic manipulation of gridmats with pvc tubes and bracing elements with straight abutment/ edge details was investigated.

This chapter investigates alternative materials of gridshell formwork to create concrete shells with double curvatures.

This chapter will be presented in three sections:

1. Construction
2. Aesthetics and
3. Structure

Fig 8.1 The Gaussian vaults of the Caputto orange factory at Salto (1972), Uruguay receives strength from double curvatures designed by Eladio Dieste

8.2 Preparatory Study model
Inducing Double Curvatures (Form-making)

Two small scale models were made by casting a thin layer of concrete over a plastic gridmat formwork from polypropylene lattice strips created by MEng students where double curvatures were induced. Double curvatures allowed additional stiffness to realise larger spans exemplified in the Gaussian vaults of Eladio Dieste (fig 8.1) in Uruguay (Pedreschi, 2000).

The gridmat model measured 300mm x 300mm in plan with a diagonal grid pattern. The laths were 20mm wide and had 20 mm grid spacing. The plastic was laser cut into strips with 1.4mm diameter holes for pins to be inserted to form rotational nodes for scissor action to take place. The gridmat was restrained at both ends as shown in fig.8.2 using a single piece of styrene lath pre-drilled with holes. The styrene member was tensioned to create a single-curved vault.

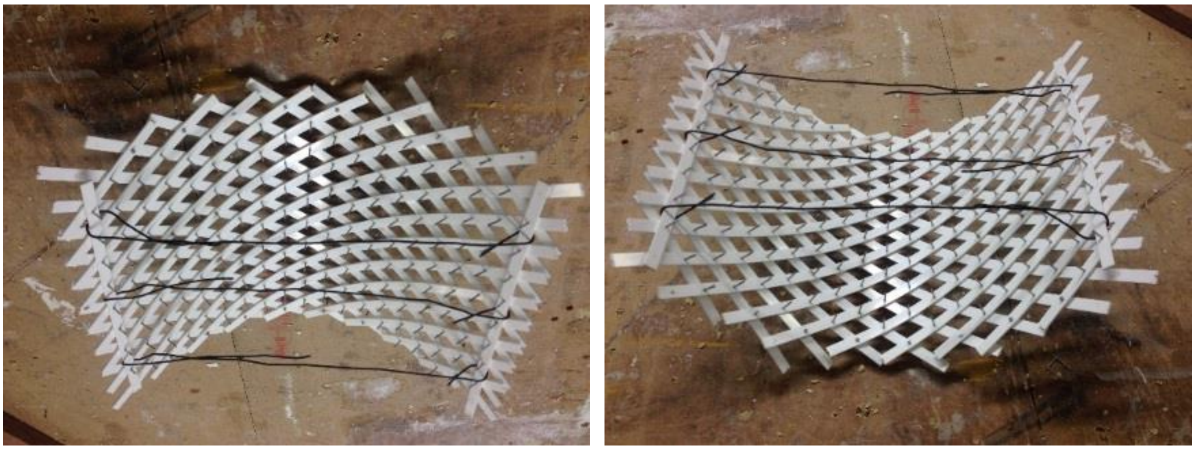


Fig 8.2 Plastic gridmat restrained to induce monoclastic vault.

As discussed in chapter 3.2.2.1, shells can be formfound in a variety of ways. This exercise describes a method of form-making (as opposed to form-finding) for “improper shells” (Candela in Garlock and Billington, 2008).

The next step involved experimenting different ways of inducing double curvatures. By manipulating the gridmat, it was possible to create synclastic and anticlastic geometries by pulling together (compression) or pushing apart (tensioning) the gridmat (fig 8.3). This geometry was secured by fixing bracing laths across the mat. It was possible to achieve a synclastic curve by pulling the gridmat apart in apex and fixing the bracing. Similarly, anticlastic curvature could be achieved by pushing the gridmat together. In these two cases, the geometry was “locked” in place by holes drilled through to retain this shape.

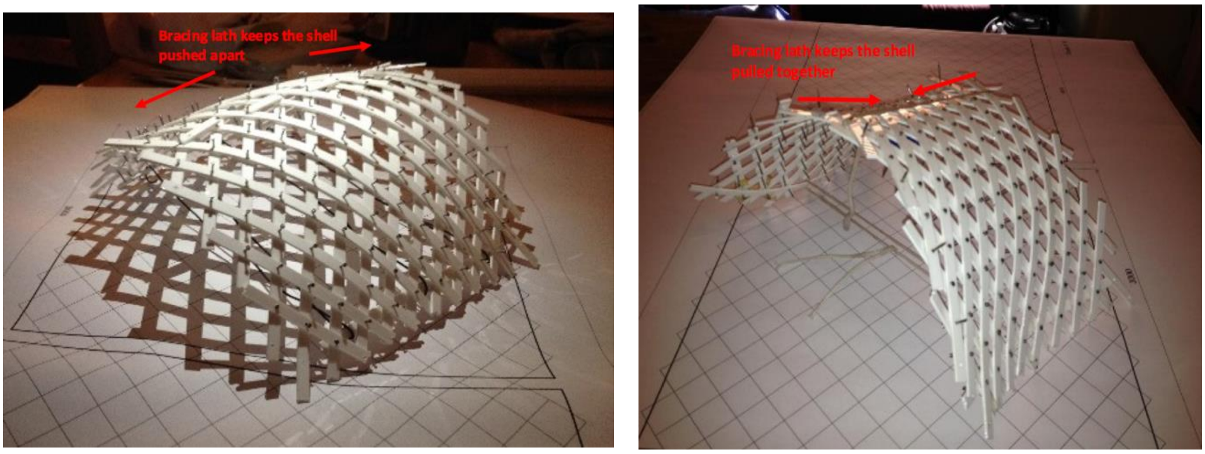


Fig 8.3 Bracing manipulation can control shell geometries

These were in turn restrained with straight timber abutments illustrated in figure 8.4 below.

Fig 8.4 Abutments

The next stage involved stretching a fabric over this formwork by laying it over the gridshell but tucked under the abutments. To stretch the fabric, their ends were wrapped around another piece of styrene strip and rotated. When the fabric was taut, the lath was secured to the abutments by pins. Laths were then added and attached to the edges to form a tray detail defining the free edges of the shell. Concrete was subsequently applied with the addition of strux reinforcement fibres in the concrete mix, with concrete successfully applied to both. After a weekend of curing, the formwork was removed easily resulting in concrete shells.

Simple doubly-curved geometries were systematically achieved and controlled. The simplification and the ability to achieve double curvatures with straight abutments impacts the ease of construction and cost.

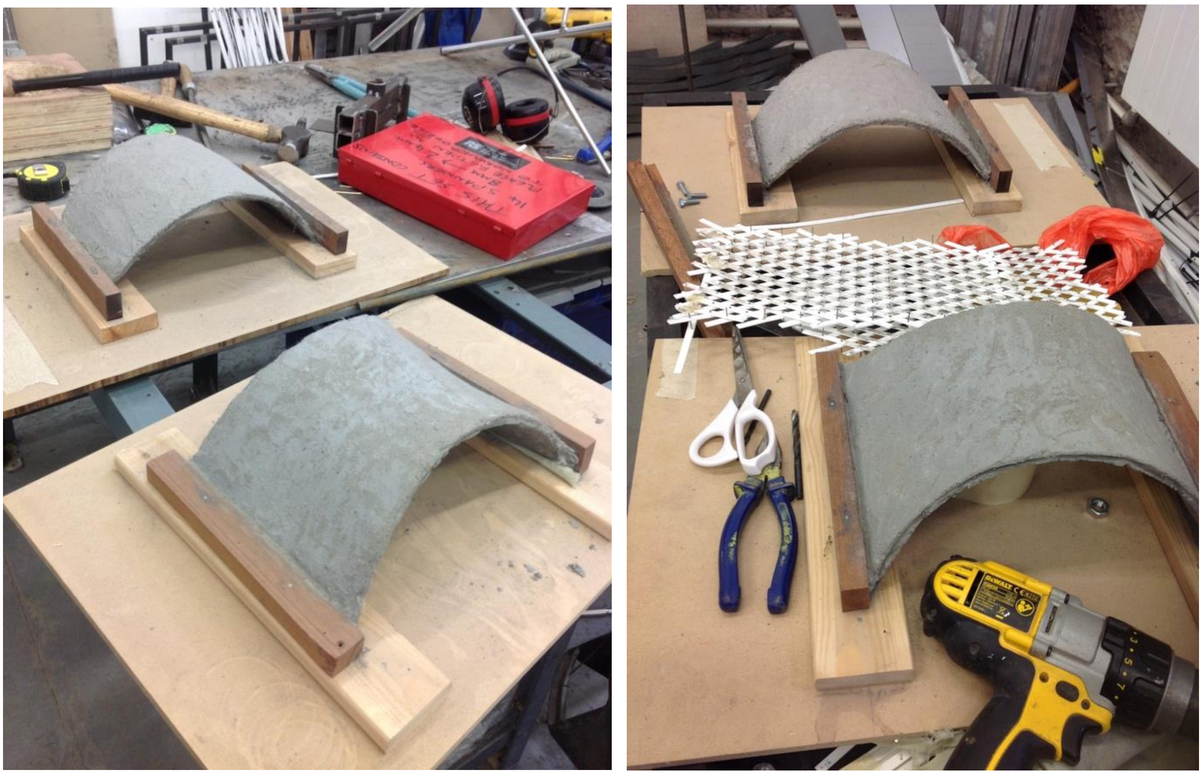


Fig 8.5 Two concrete shell models were constructed from the same gridmat with the same abutments but with different shapes.

8.3 Test

Construction of a concrete shell at a 1:1 scale

A 3m x 3m gridmat was fabricated with the longest lath measuring 4.2 m. In the previous experiment, pvc (oval conduits) 16mm x 10mm allowed the shell to curve in a single direction easily but was difficult to connect and extend.

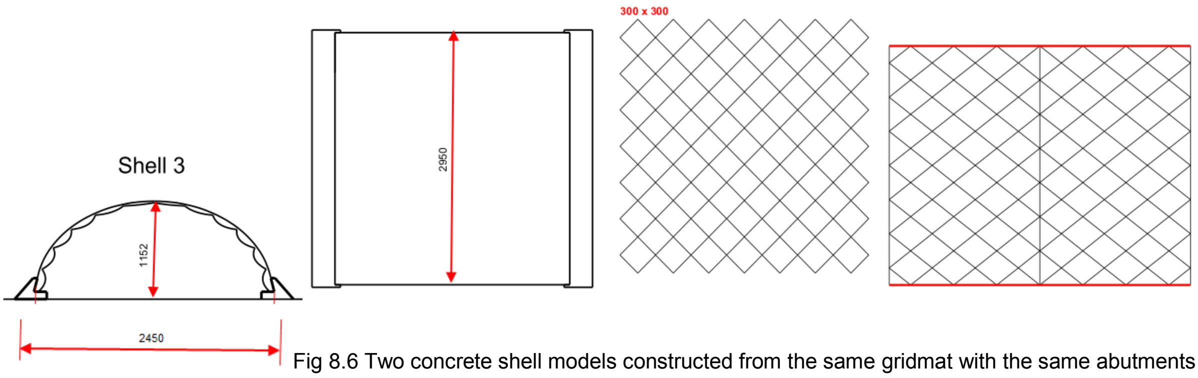


Fig 8.6 Two concrete shell models constructed from the same gridmat with the same abutments but with different shapes.

8.3.1 Potential Materials include:

- Steel

  25mm wide strips were cut and bent easily. Although longest lengths measured 2m, extending these was carried out by riveting two pieces together (fig. 8.10). The disadvantage of steel rests on their propensity to buckle and low yielding point. They are however low cost.

- Carbon fibre

  This material is stiff (did not bend easily), brittle and shatters. It is costly as well - a metre length of carbon fibre tube - 8mm x 4.7mm cost £8.95 + VATS (www.ecfibreglasssupplies.co.uk)
- Fibreglass tent rods

  This tent rod material was selected for lightness, flexibility and strength. Connected by steel connectors to form various lengths, circular and hollow in section, the sections bend in various directions. Their circular profiles present similar difficulties experienced by bamboo laths used during the student construction workshop in Denmark (Chapter 5.6.1) of bracing intersection or scissoring. GFRP tubes cost less than carbon fibre tubes - 8mm x 4.7mm cost £3.25/m + VAT (www.ecfibreglasssupplies.co.uk)

8.3.2 Abutments

The abutment design was simplified from test shells 1 and 2. The pair of abutments was pre-cast in a laser cut mould made from mdf panels and bolted to the concrete screed floor 2450 mm apart from each other. Each concrete abutment measured 3m long. The mould was prepared by laser cutting 300mm x 400mm sheets of MDF boards. Using duct tape, strips of aluminium were taped together to form the mould into which concrete was poured. 10mm diameter steel rods were also cast into the abutments (see fig. 8.7).

Fig 8.7 Casting the concrete abutments

Fig 8.8 Concrete abutments were constructed by taping mdf sheets together to form a mould.

The shell concrete was mixed at the ratio of 1 part (cement), 2 parts (sand), 3 parts 20mm aggregate). No reinforcement bars or meshes were used. On hindsight, it may have been better if the abutment were cast in shorter sections as when the abutment was attached to the uneven ground, it cracked into three separate parts. The concrete abutments were attached onto the concrete floor permanently at the correct position that could not be moved. The abutments were placed 2.450 mm apart and 1.4 m below an I-beam from which a hydraulic jack was attached for testing afterwards.

8.3.3 Steel gridshell

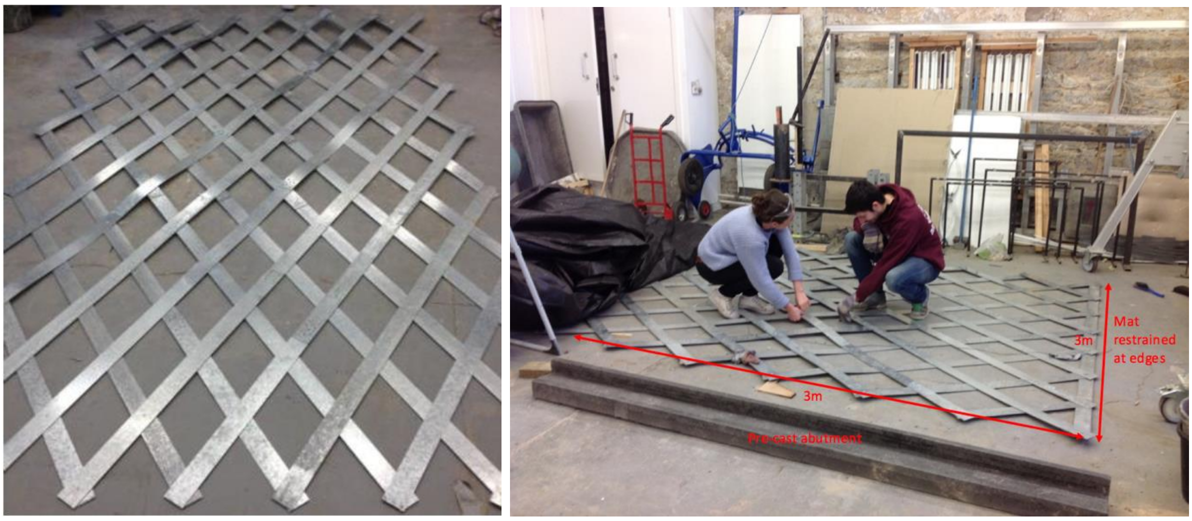


Fig 8.9: the metal grid-mat being assembled.

The steel gridshell mock-up formwork was scaled-up by a factor of 10 to one measuring 3m by 3m. The grid spacing also increased from 200mm to 300mm. In total, 34m length of 2mm thick 70mm wide steel strips were guillotined and spliced to form long lengths. Two steel laths were riveted together with 4 overlapping rivets to extend the lath. These areas of overlaps had to be minimised to prevent the gridmat becoming excessively stiff. The laths were then drilled at 300mm centres with 50mm left from the ends. Rivets also formed scissoring pin joints. It was found that by pushing the gridmat into a vault shape was easily possible; however the tight swivel rivet joints caused lath members to buckle locally. Therefore, to encourage scissoring at intersecting nodes, washers were introduced between strips to prevent steel members locking due to friction caused by uneven edges of holes. This allowed free rotation to achieve the required deformation.

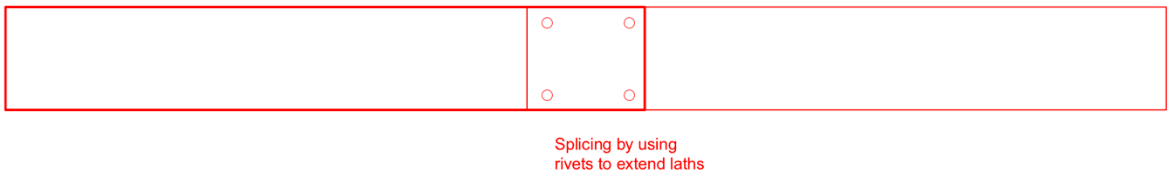


Fig 8.10: Splicing/ Extending joint

Initially, holes were drilled by a template. However, following continuous drilling, holes on the master template were eventually enlarged and became inaccurate. Drilling by hand meant (compared to if the machine was laser cut) holes were aligned better with a few mm off eccentricity for the holes.

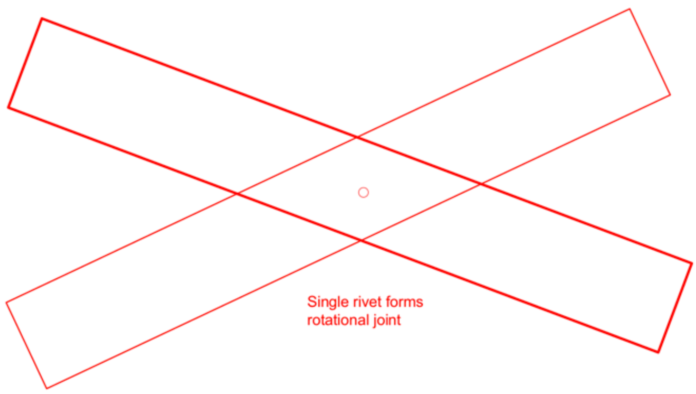


Fig 8.11: Rotational/ swivel joint

Swivelling pin connections were made with 4.8mm x 30mm rivets – A4 stainless steel dome rivets with 6mm washers. The pre-drilled lath sections were first laid out on the floor according to the predetermined mat. Rivets were attached by lifting the metal sheet laths away from the ground. It was observed that some of what were supposed to be an “overlapping holes” did not line up. Some holes had to be re-drilled. This eccentricity caused problems such as compression/ buckling behaviour giving rise to snagging during the eventual deformation process. The soft and malleable nature of the steel sheeted laths also made the gridshell difficult to manipulate.

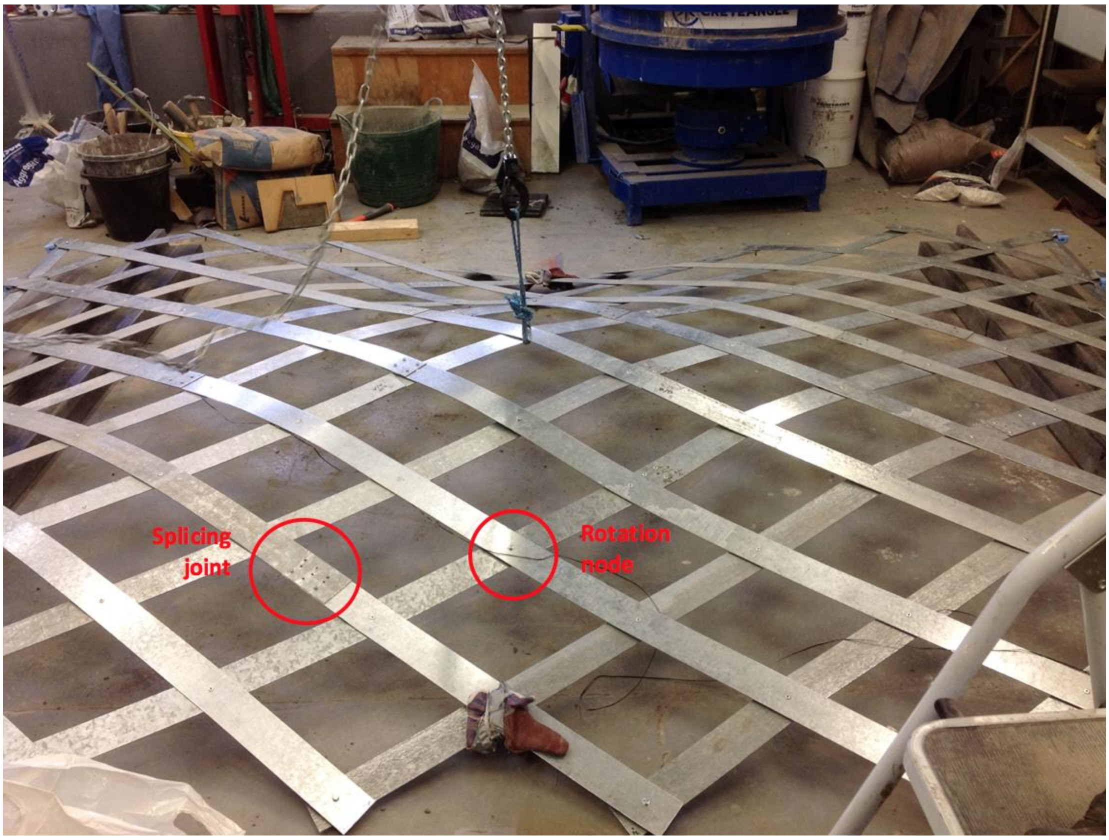
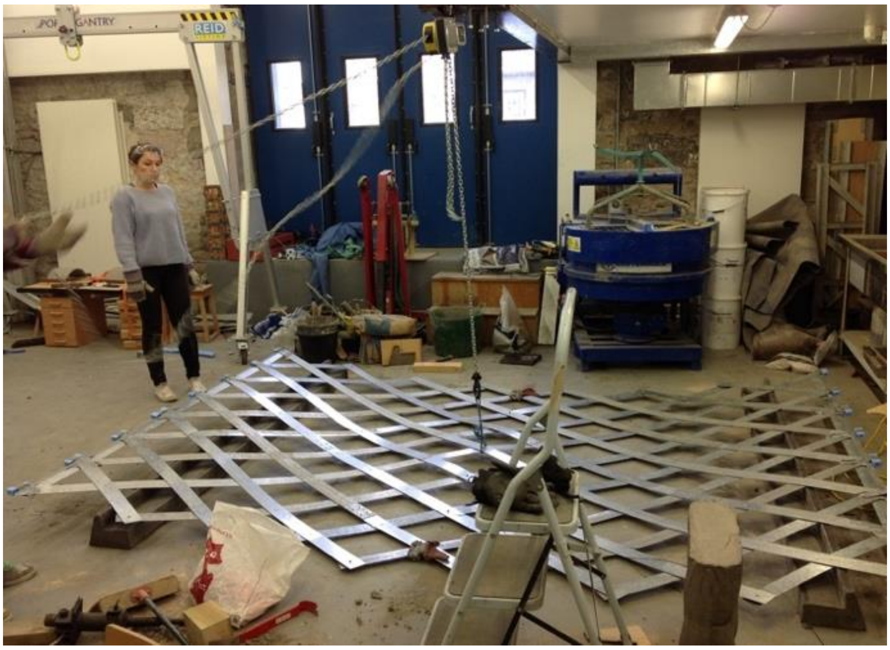


Fig 8.12 Gridmat was lifted by a crane at the middle of the mat. Visible are the different rivet arrangements- splicing joints consisting of four rivets extend the metal laths and rotation node which consisted of a single rivet. To avoid eccentricities, these single nodes were made in the middle of each crossing lath.

8.3.4 Forming the anti-clastic gridshell formwork

Firstly, the metal gridmat was placed in position under a lifting jack. At the initial trial, an attempt at extending the gridmat was made. It was difficult to do this as the gridmat was very stiff. As such, it was elevated above ground by small amounts to deform. The metal gridmat was heavy, rigid with sharp edges. As significant bending and buckling were noticed, promptly, the mat was lowered to prevent irreversible local deformations. During the second attempt, the structure was jacked into position with someone supporting the lifting point to prevent buckling the gridshell.

Once the mat sat within the support of the abutments, a synclastic shell (dome shape) was created. However, to achieve an anticlastic saddle-shape, the gridmat had to be manipulated and reshaped (fig 8.12 a and b).



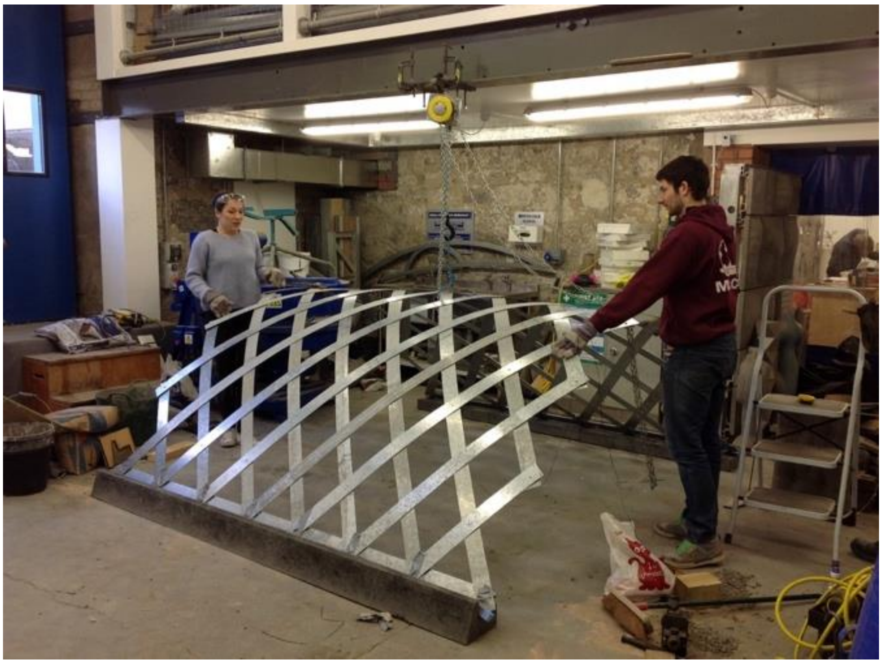
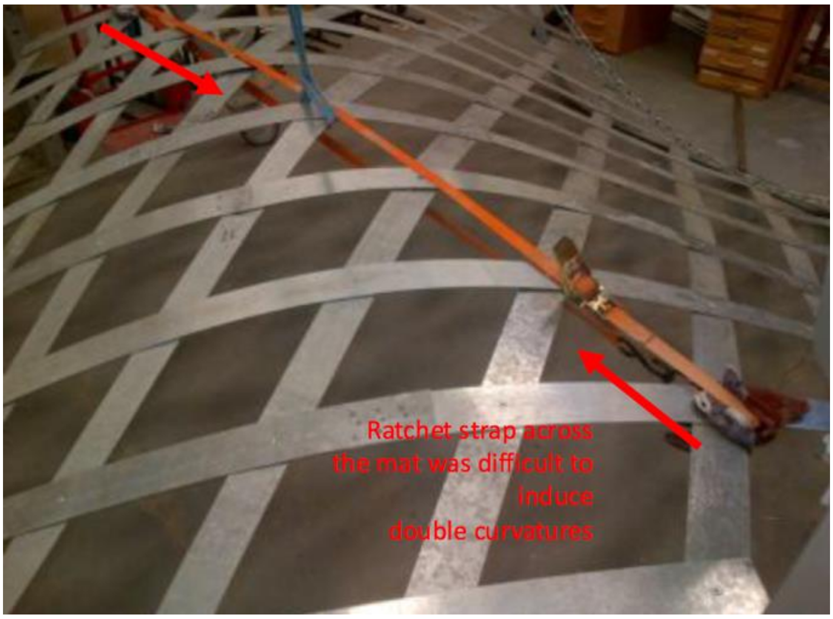


Fig. 8.13: a) left: The gridmat was lifted into shell shape with much difficulty.
b) right: once the shell sat within the abutments, adjustments to the geometry began.

Ratchet straps were employed to encourage the gridmat to deform into an anticlastic shape. Instead of manipulating the entire mat, it was more effective to deploy smaller regions in the mat. By localising compression through shortening two grids each time (instead of the entire length), the gridmat deformed and produced an anticlastic (saddle-shaped) gridshell of double curvature with anticlasticity. In total, four ratchet straps were used to pull together the middle fragments of the gridshell. When deformation was complete, the gridmat diagonals at the centre of the shell measured 20cm less than those at the ends longitudinally (i.e. along span direction).



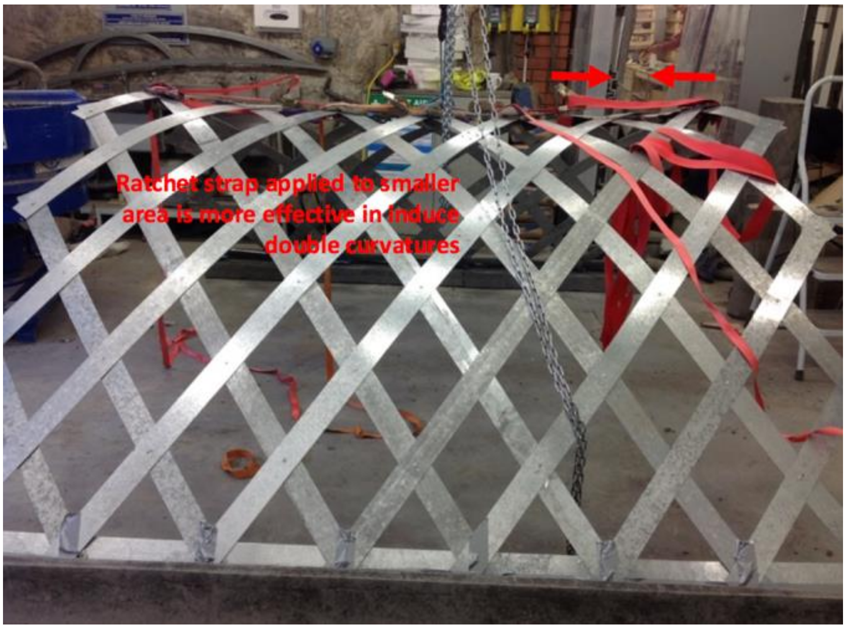


Fig 8.14: Ratchet straps were used to pull the apex together to induce a double curvature with much difficulty and buckling tendency from the flat material. a) left: Using ratchet straps across the entire shell did not help to bring about desired shell anticlasticity b)right: Ratchet straps applied across small distances e.g. 2 grids was more effective in deforming the gridmat.

With the deformation stage complete, metal bracing pieces (75mm wide and 2mm thick metal strips) were riveted onto the gridmat across the shell to freeze the geometry. The mid-span apex was restrained by riveting strips. Drilling a metal strip without any backing support was difficult and resulted in inaccurate node locations. As well as that, the diagrids were pushed. This was similarly experienced at Weald and Downland gridshell when ratchet straps were used to produce d more pronounced curvatures at Weald and Downland gridshell (Harris et al 2003).

In this example, flat metal strips were ineffective as squeezing the entire mat together at the edges did not produce double curvatures readily as in earlier plastic models. The metal strips were sharp, making them dangerous to work with. To triangulate and brace the structure, each distance between points on the edges was measured, drilled and bolted for lateral/ shear stability. The free ends i.e. abutment edges of the gridshell were also joined up this way (fig 8.14). The material required a high degree of accuracy which was difficult to produce as these metal strips were drilled whilst in position.

Fig. 8.15: The gridmat was lifted into shell shape with much difficulty and deformation had to be forcefully encouraged.

Fig. 8.16: The double curvature anticlastic double-curved shell was created eventually. Top: edges are secured using rivets in the same way laths were extended

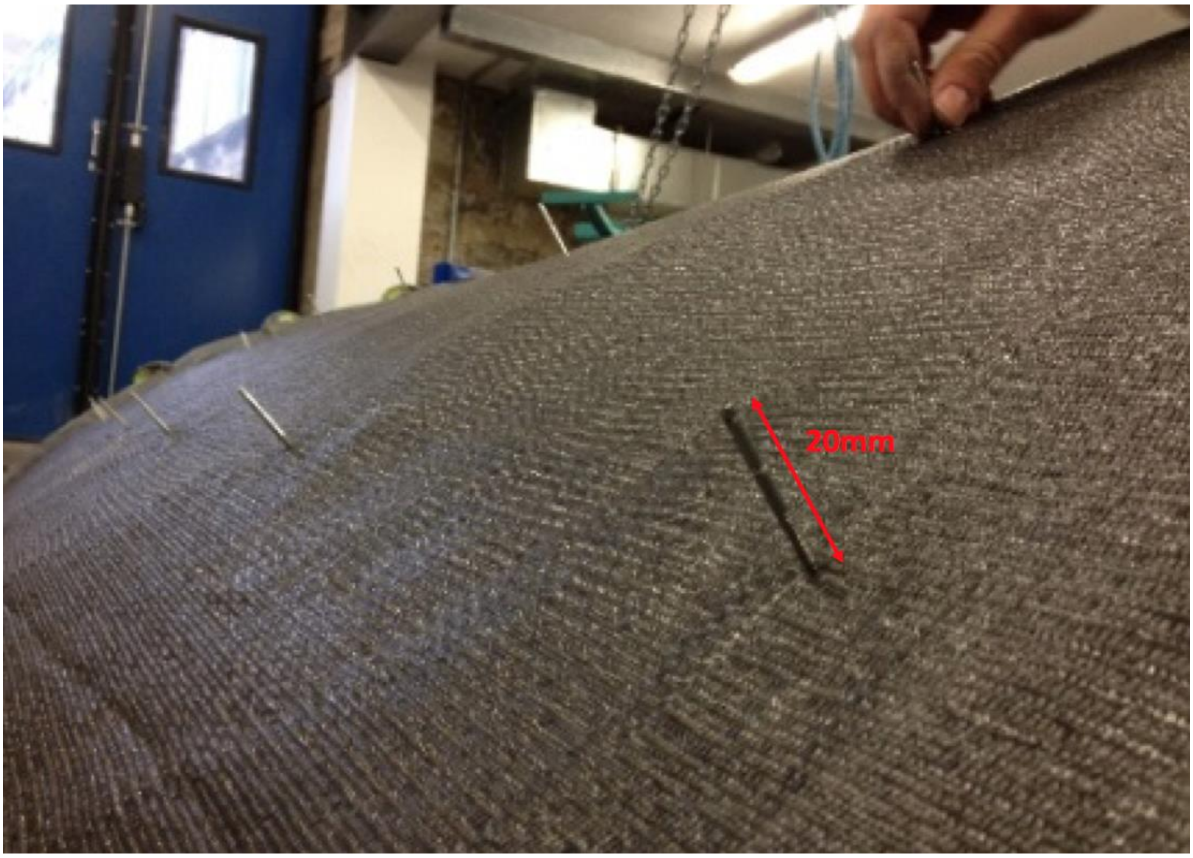
Subsequently, a woven polypropylene fabric was stretched over the surface of the shell with a spare 50cm margin. Just like the small scale mock up, this fabric was tucked underneath the metal gridshell.

One edge of the fabric was wrapped round a timber batten and affixed securely to the abutment whilst the free side was secured to a L-profiled steel bar and spooled round to tighten the fabric covering. The gridshell had to be lifted slightly and be taken from underneath the gridshell to stretch the fabric as tight as possible. It required the co-ordinated efforts of 2 persons to tighten the fabric this way (fig 8.17).

Fig. 8.17: the fabric was wrapped around a wooden batten to tighten the fabric against the gridshell before concrete was poured.

Fig. 8.18: The gridmat was lifted into shell shape. The edges were defined by a 20mm square polystyrene section.

The sharp corners of the gridmat which rest on the concrete abutments were taped to protect and prevent the membrane from being punctured. The free edges were also lined at the top edge with 20mm x 20mm polystyrene strips (fig 8.18 right) to create a defined concrete edge by securing it with clamps so that the gridshell could be covered with an even layer of 20mm concrete.



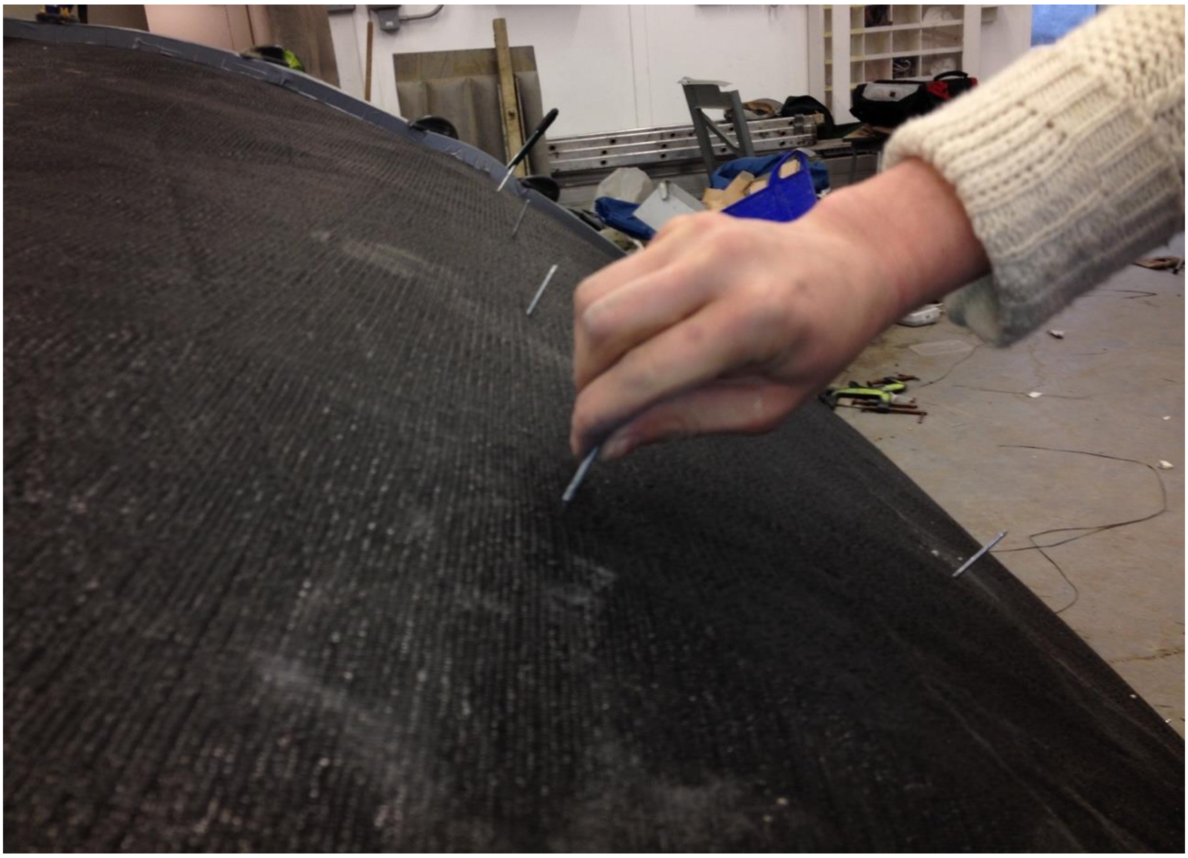


Fig 8.19 To further control and create a shell with an even thickness of 20mm throughout the shell, remaining section of the rivet cut to a length of 20mm was inserted back into the rivet hole. These were the waste product which acted as a thickness guide.

8.3.5 Concrete Mix

The concrete consisted of 1 part cement to 2.5 parts sand. Two separate batches of concrete were mixed from 125kg sand and 900g of 40mm Strux 90/40 Synthetic Macro Fibre reinforcement with approximately 8 litres of water. The shell was cast in 2 layers, each approximately 10mm thick. The first scratch coat was allowed to cure for 1 hour before the second layer was cast over. This was completed to reduce cracks. The formwork did deflect under the weight of the concrete. To support this, timber posts were introduced as temporary supports (fig 8.20).

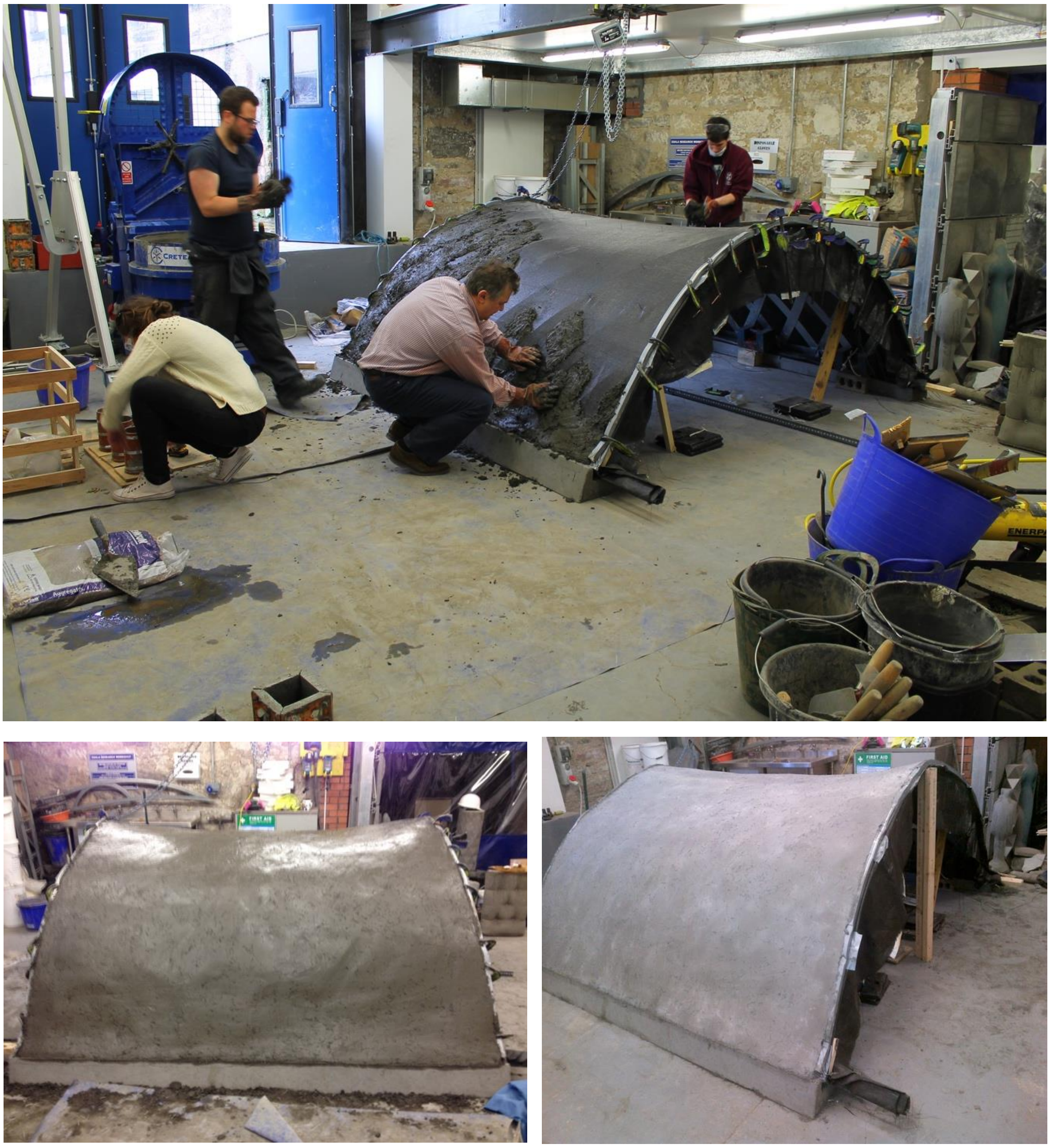


Fig 8.20 Casting the shell required timber propping.

8.4 Construction

8.4.1 Casting

A flat material, the metal strips held lateral stiffness, unyielding to applied deformation forces, resistant to produce double curvatures. As the shell was only braced at three locations – across the apex and near the 2 abutment edges, the formwork lacked rigidity.

To check for double curvature, a straight timber plank was used to detect double curvatures resting between free edges at the apex. The check revealed a span to rise ratio of 2.13: 1 at the free edges with a sag of 9cm in the middle of the gridshell formwork. It was noticed that the shell sagged even more when the concrete was applied until timber props were attached. At regions closer and parallel to the abutments, cushions with increased thickness closer to the abutments were observed.

Permanent local buckling was observed within the metal gridshell. When the gridshell geometry changed, some rivets had to be replaced with bolts so that restraining strips could be added when the gridshell was shaped and placed onto abutments. It quickly became necessary to increase the hole size by redrilling. This misalignment proved problematic when restraining/ bracing members were attached onto the gridshells to brace the structure.

To form the gridshell, diagrids were pulled closer together by shortening ratchet straps. During this process, the metal strips actually buckled under torsional forces. The sharp edges of the metal strips also ripped the fabric. It was very difficult to stretch the fabric tight.

Like the previous shells, concrete was first applied at the abutment sides, progressing towards the crown with a second concrete layer. Secondary timber props were installed during the casting process to support the formwork and ensure heights of key points. These timber props were placed at mid-span and at quarter-spans which were found in previous experiments to be key in shell casting. Due to shell size and dimension, it was difficult to reach across to the centre of the shell to apply the concrete.

The process of hand trowelling on concrete was time-consuming and laborious, taking a total of a full day 8 hours) by 4 people to apply.

Although the scale model was easily deformable, the scaled up version was difficult to activate. This can be attributed to the difference in shape and proportional cross-section of the model (5mm x 2.5mm thickness) compared to flat ribbons of steel which were susceptible to local buckling.

8.4.2 Decentring

Unfortunately, when it came to removing the formwork, the metal shell was trapped under the concrete shell and was damaged during extraction. The formwork was destroyed and could not be reused, rendering this material system unsuitable for re-deployment. The metal gridshell was dangerously sharp to handle as well with the swivelling effect replicating the snipping action of a sharp pair of scissors!

To extricate the gridshell, bracing sections were first detached by removal from beneath the concrete shell. Secondary support in the form of poles had to be installed to hold up the gridshell temporarily. When the metal bracing was removed, the metal gridshell refused to become free from the concrete shell as it was trapped under the concrete shell.

However, it was immediately observed that cushions were much shallower and less pronounced than the previous concrete shells (test shells 1 and 2) made from plastic conduits. Rivet pins installed into rivets before casting had ensured an evenness of concrete in the resultant shell.

Fig 8.21 The imprints of the metal plated gridshell again clearly created an interesting cushioned appearance.

To remove the gridshell, it was necessary to apply great force to remove the formwork. It also took comparatively much longer than test shells 1 and 2 to dismantle (each taking less than 10 minutes to remove). Tugging and pulling the sharp-edged gridshell from under the concrete shell caused damage. In fact, test shell 3 cracked as a result (see Fig. 8.22).

Fig 8.22 Imprints of the metal gridshell again created shallow concrete cushions as expected with the mangled metal formwork

Importantly, this difficulty saw permanent gridshell deformations which rendered formwork un-usable and unsafe for this application unless modifications were made to the construction system.

Fig 8.23 Bracing strips were removed first to liberate the concrete shell from the gridshell. Temporary props at mid-span support key sections of the shell.

The metal gridshell was trapped mainly at the bottom abutments. Eventually, an angle grinder had to be used to extricate and remove the metal gridshell formwork. Metal strips was difficult to be used as gridshell formwork for casting concrete shells. The flat metal plates provided shear resistance that prevented the shell from producing double curvature formations.

A possible use of the metal gridshell as formwork would be to leave the gridshell in situ to act as sacrificial formwork visible from the underside similar to how the Japanese architect Shoei Yoh allowed bamboo formworks to be exposed at the concrete roof at Naiju Community Centre, 1994 (Chapter 6.7.2) and Uchino Community Centre in Fukuoka, Japan 1995. Compared to previous gridshell constructions in timber and pvc tubing, this metal gridshell was rigidly tight and did not rotate and deform freely.

To completely remove the metal gridshell, the process took 1 hr 30 mins. Compared to Test Shells 1 and 2, the decentring process for Test Shell 3 was complicated and challenging. Eventually, angle-grinder had to be used to extricate the formwork completely in numerous mangled pieces. As such, the crushed metal strips could not be reused again. These challenges emphasized the importance of correct material choice and importance of decentring design/ consideration.

8.4.3 Safety

The riveting machine caused a tightness of rivets making gridshell deployment difficult. Additionally, metal laths were sharp and coupled with a difficulty to manipulate and deform the gridmat without buckling, it made the process challenging and unsafe.

8.5 Aesthetics

Fig 8.24 The mangled metal gridshell could not be reused.

Once the metal gridshell was removed, it was possible to peel away the black formwork fabric to reveal the fresh concrete shell. Compared to shell 1 and 2, the underside was smoother and finer than Test Shells 1 and 2.

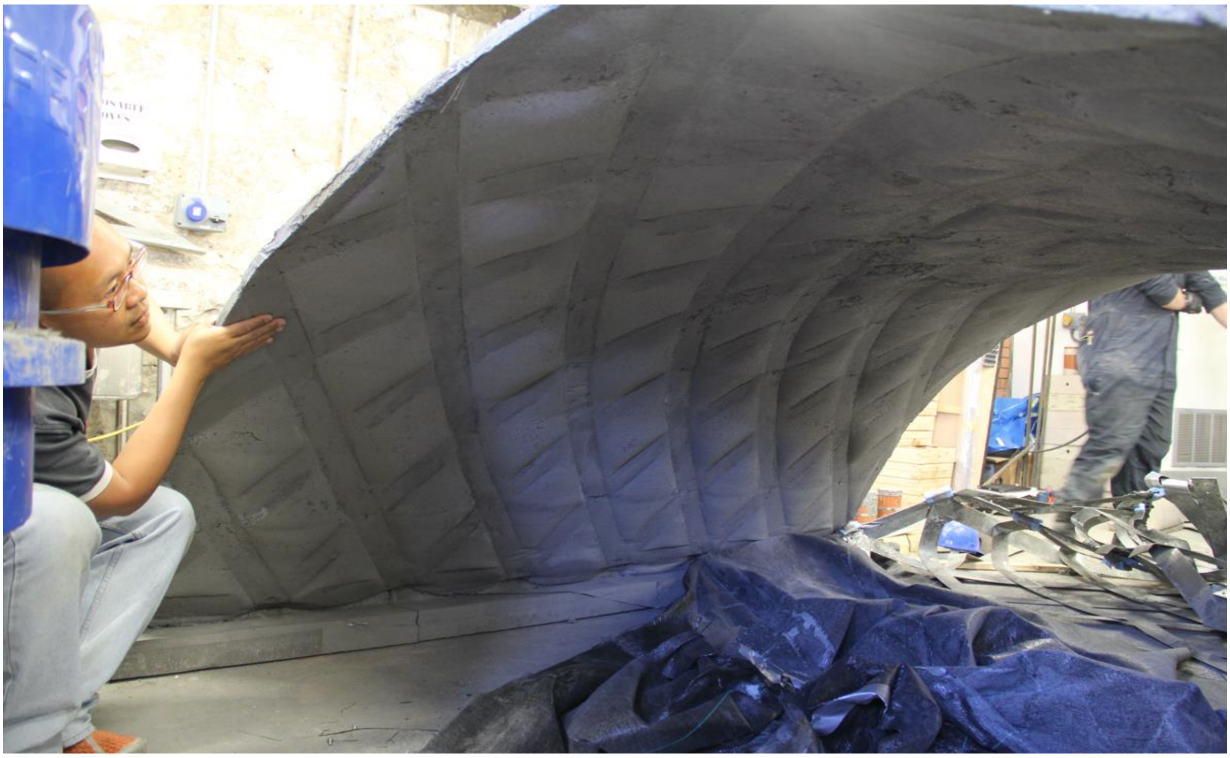


Fig 8.25 (top) Imprints of the Shell 3 metal gridshell. (bottom): the rougher undersides of shell 2.

The thinness may be due to the flat metal ribbons cutting less into the concrete gridshell allowing a thinner layer of concrete to be applied with the checking of 20mm thickness guides. With the fabric more tightly stretched than Test Shells 1 and 2, a smaller variation of thickness was achieved. Measurements taken at key points showed a minimum thickness of 20mm and maximum thickness of 40 mm at the thickest cushioning. The visual effect had less variation i.e. more consistent and even than shells 1 and 2. The key measurements also meant the shell thickness variation to span ratio reduced to 0.67% from 4% for shell 1 and 4% for shell 2. This means it was easier to control thickness evenness despite the difficulty to deform three-dimensionally.

8.5.1 Cushions and Indents

The imprints of the metal plated gridshell created an interesting cushioned appearance, evidencing a stereogeneous technology (Manelius, 2012). The idea of the grid-frame is very clearly expressed in the aesthetic of the resultant concrete shell. Examining the junction between the abutments and the shell, it is clear how removing the gridshell from abutments was problematic. The plate nature of the formwork was locked between the tight abutments and shell. After 100 minutes of cutting up the metal frame and pulling away the gridmat from the concrete shell, trails of fabric fibres were trapped and became visible in the concrete structure itself.

Fig 8.26 Imprints of the metal gridshell again created shallow concrete cushions expressed on the inner underside revealed after the fabric was peeled away.

8.5.2 Concrete Finish

Concrete quality for Test Shell 3 was better than Test Shells 1 and 2 as it had less blow-holes and imperfections (see fig. 8.26). Although they were mixed in the same proportion, the casting process of rubbing on the under-surface helped to bring the cement up to the top surface to produce a finer finish. Also, the black fabric may have allowed air to escape more readily. Additionally, the concrete mix is also more viscous in Test Shell 3.

Fig 8.27 The shell have an even thinness of 20mm.

Fig 8.28 The shell had a crack developing, possibly due to the invasive nature of metal formwork extrication. This hairline crack did not follow the lines of the metal gridshell.

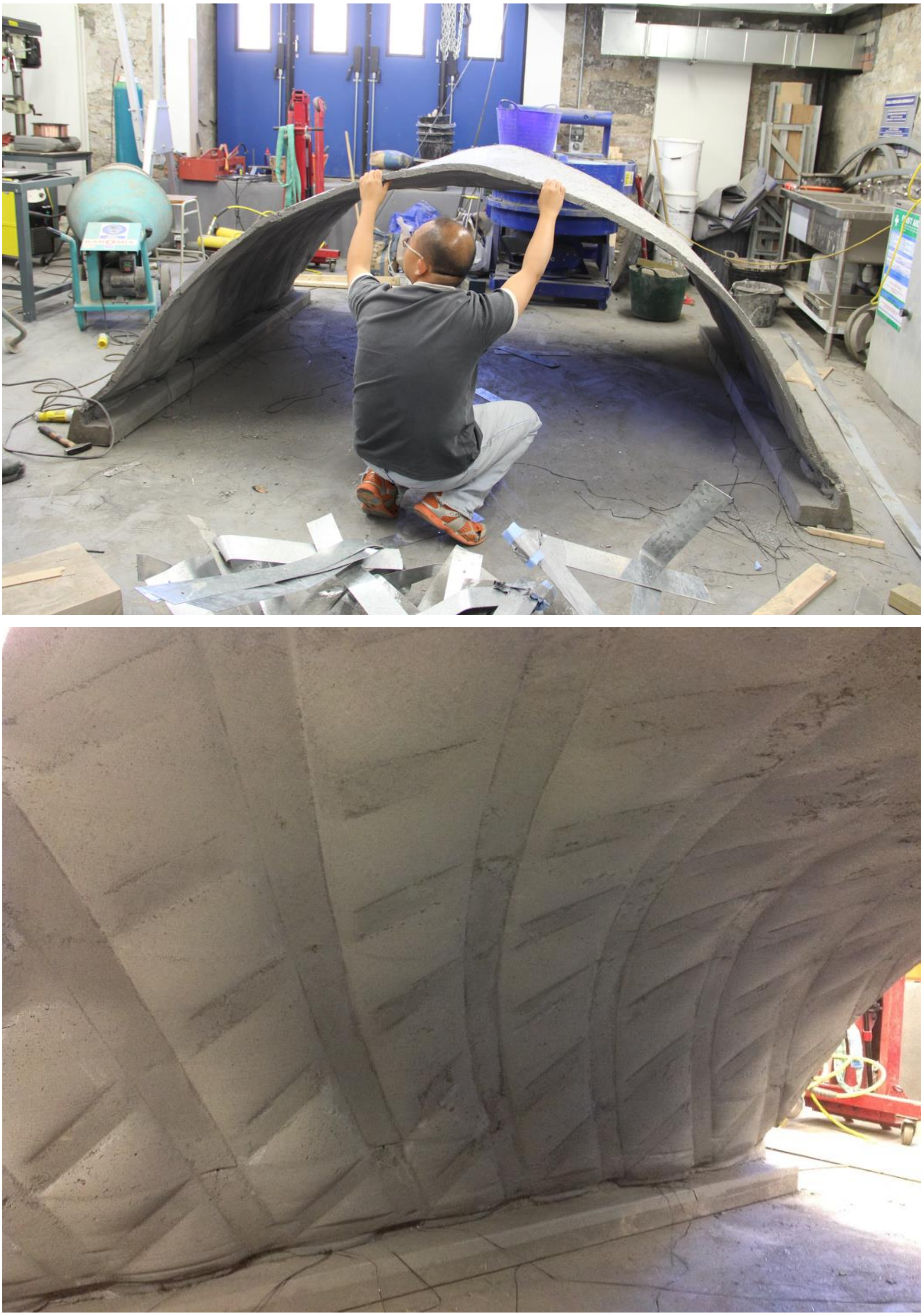


Fig 8.29 (top) The shell is expressly thin and at the edges had a consistency of 20mm.
(bottom) Remnants of black fibres are trapped within the concrete shell.

Visually, with 20mm guides, the shell was thinner and cushions were shallower and therefore could have less dead-weight in the form of undulating cushions. Notably, there appears to be less dominant lines in the concrete shell as a result of metal gridshell use, producing a more even appearance in the aesthetics of the shell.

In this case, the flatness of the gridshell appeared to act as a stencil described by West (2016) and Manelius (2012). The protrusion of the fabric that pushed through the spaces between the flat gridshell formed 20mm flat cushions. The appearance of these shallow cushions is similar to the draping of fabric formwork pushing through stencil-like form work in fabric formed beams investigated by Lee (2011).

8.6 STRUCTURE

8.6.1 Geometry

For the purpose of testing a new gridshell material, shell thinness is not the key focus.

However, some key dimensions were measured and recorded.
The metal gridshell spanned a distance of 2450 mm, measuring 1152mm on the free edges and a discernible lowering in the middle of the shell 90mm lower (sag) than the two free edges/ sides described in fig. 8.29. It has a span to rise ratio of 2.13: 1.

When the shell collapsed, sections of the shell were measured for thickness and they measured between 20 and 40mm in thickness with a prevalent tendency of thickness at the lower sections near abutments as a general observation.

Fig 8.30 Key dimensions of Test Shell 3

8.6.2 Deadweight calculation:

Volume of concrete (lower range: shell thickness of 2cm) : 2.95m x 2.95m x 0.02m = 0.174m3

Weight: 0.174m3 x 2400kg/m3 = 417.72kg

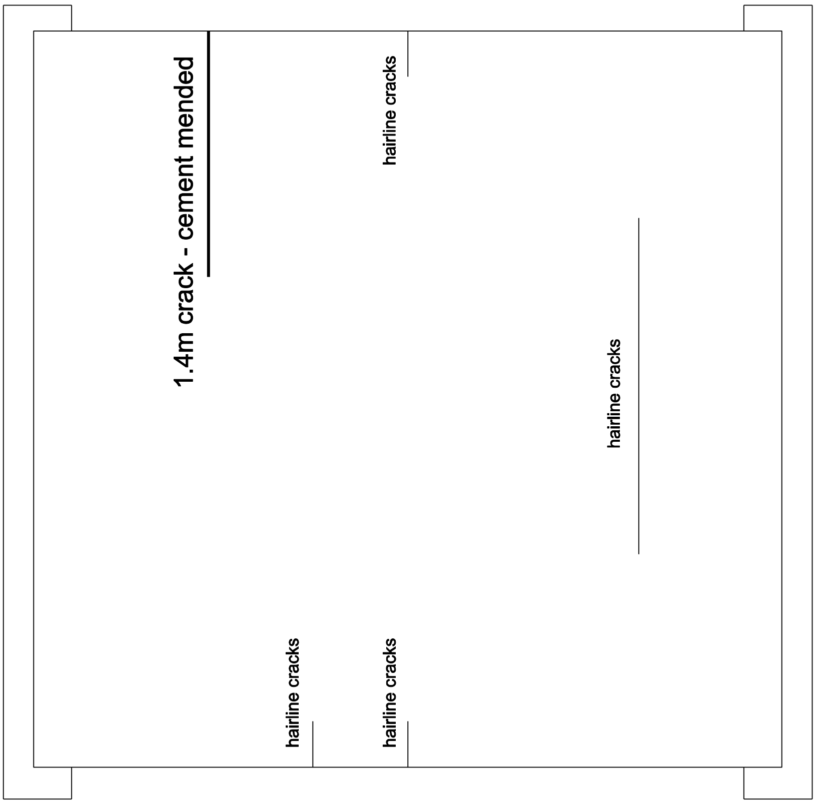
Volume of concrete (upper range: shell thickness of 4cm) : 2.95m x 2.95m x 0.02m = 0.348m3

Weight: 0.348m3 x 2400kg/m3 = 835.44kg

8.6.3 Failure mode

The experiment was set up using the same principles applied to failure testing experiments for Shells 1 and 2. The method consisted of steel spreader bars welded and arranged to produce 4 point loads along the mid-span ridge along the shell apex described in the figure above. The pre-planning of test shell 3 located it directly underneath the hydraulic arm i.e. the edge of the mezzanine in the Edinburgh University concrete research workshop, meant that unlike test shell 1 and 2, it did not need to be moved, which would have subjected it to accidental deflection.

Fig. 8.31 (top) crack 2 clearly visible and repaired.
(bottom) concrete shell collapse.



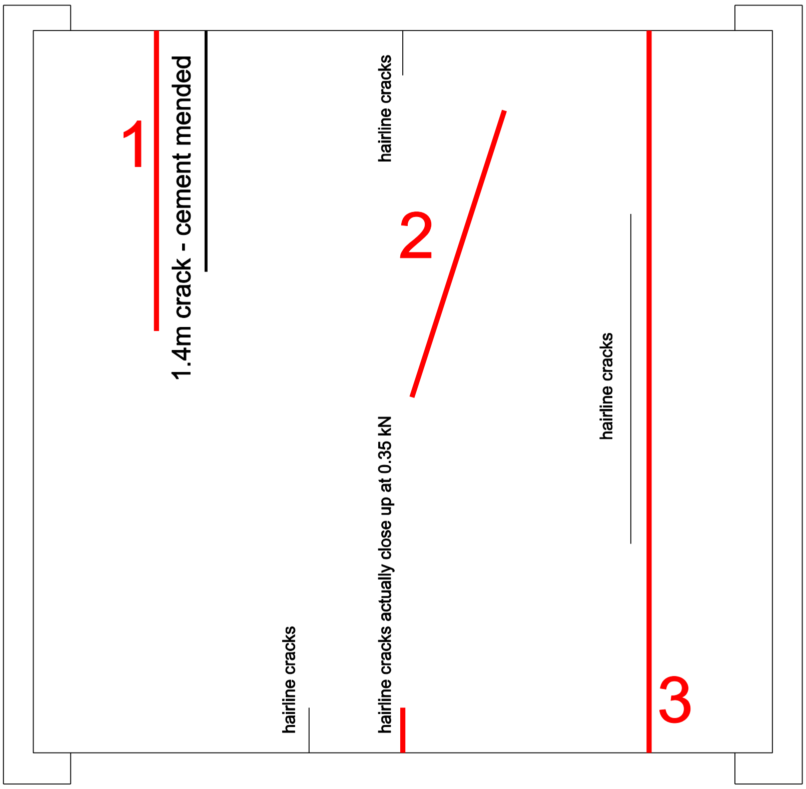


Fig. 8.32a) top: Locations of cracks (on external surface) before load test
b) bottom: Sequence and location of cracks (on the external surface) during and after load test

8.6.4 Visual assessment.

The shell measured 2950mm wide by 1152mm high at the free edges. The geometry is slightly more pronounced developing a synclastic saddle shape, designed and expected in the design of the shell.

Fig 8.33 A pre-testing crack measuring 1.4m repaired with cement.

Before the start of failure loading, cracks and fissures were visible in the shell itself. This is described in fig. 8.33. The most obvious crack measured 1.4m longitudinally from one free edge to another. It was repaired using a cement mix. There were also a number of smaller cracks (fig. 8.32) visible near to the free edges of the concrete shell on both free edges. These cracks did not follow the indentation of the gridshell formwork indentation underneath. A larger crack developed at the quarter span location indicated by 3.

When this occurred, the shell edges lifted upwards. This positive upward and outward displacement was the result of the middle section depressed downwards. The cracking sound was due to the splitting of the concrete at the free edges.

Fig 8.34 Cracks at the edges of the shell during failure loading.

When forces were imposed, no movement or deflection was observed. At 0.41kN (i.e. 41kg), a loud cracking sound could be heard. At this point, a long split was observed to run along the entire longitudinal length of the shell at crack 3. Also, the shell fractured at region 2 (see fig 8.31) under the influence of the load spreader. When crack 2 appeared, the entire shell quickly lost load resistance and the entire structure very quickly gave way and collapsed. This represents a failure mode to self-weight ratio of 9.8% to 4.9%. Compared to the ratios for Shell 1 (393%) and Shell 2 (432%), this value is small.

Upon applying a further force, at 0.51kN, the entire shell gave way completely and collapsed in sections. Like shells 1 and 2, strux elements helped the structure to hold itself together after cracks and fissures appeared (see fig 8.34). The collapse was less ductile and faster when compared to shells 1 and 2. This was due to the substantial deadweight of the shell.

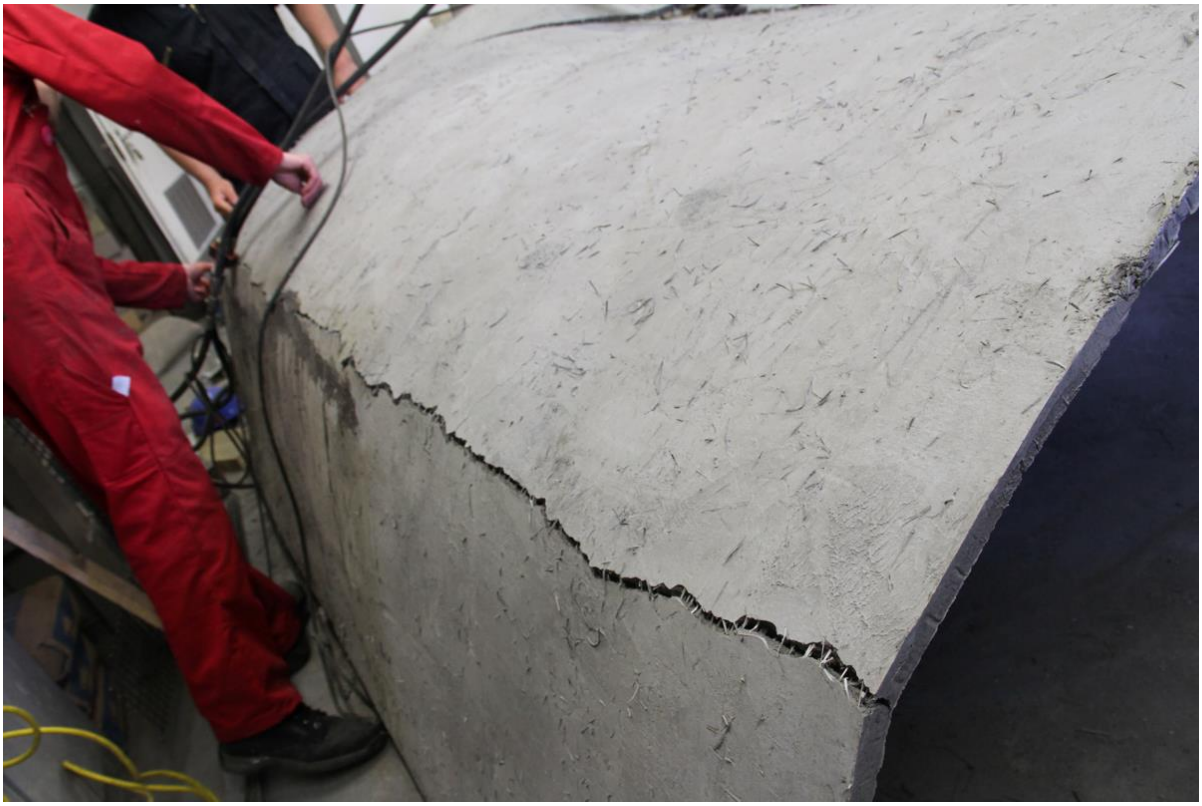


Fig. 8.35: Crack 3 develops through the shell at quarter span.

Fig. 8.36: The entire shell drops and breaks into pieces

Compared to test shell 1 and 2, the failure behaviour for test Shell 3 was much more plastic. The deformation was much more localised and did not spread completely. This was possibly due to the size of the shell compared to the area whereupon forces were applied. As such, it appears this arrangement may have yielded localised loading instead. This has resulted in the observation that the shell was broken at the top of the shell. The shell then imploded at the top sections before collapsing and giving way completely.

8.7 Discussion

8.7.1 Cracks

It is possible the cracking and fissures had developed within the thin shell structure before the failure test. These cracks may have been the result of the removal of the metal gridshell, difficult to collapse and deploy, especially within a very constricted space. This emphasised the importance of a system which is easy to de-centre.

Fig. 8.37: The abutments were lifted out and off the ground

8.7.2 Abutments

The low failure capacity was also influenced by abutment situation. The abutments prevented the shell from collapsing into the area outside the abutment curtilage. It was observed that moments were large as buckling caused the abutments to be raise up from the ground before collapse described in fig 8.42. If the abutments were completely attached to the ground, applied forces may be able to be transferred into the ground much more efficiently. This emphasizes the magnitude of stresses present at shell footings requiring structural attention to resist large bending moments

8.7.3 Aesthetics

The photograph series below captures the failure fracture where the shell began to fail. This happened at the quarter spans. The shell began to lean towards the right hand side, but in this case, had been restrained by the abutments from falling over. This region attracted much compression forces to cause the entire shell to collapse inwards.

Fig 8.38 The 1.4 m long fissure is also visible from the underside.

Fig 8.39 The fissure developed across the shell at mid-span.

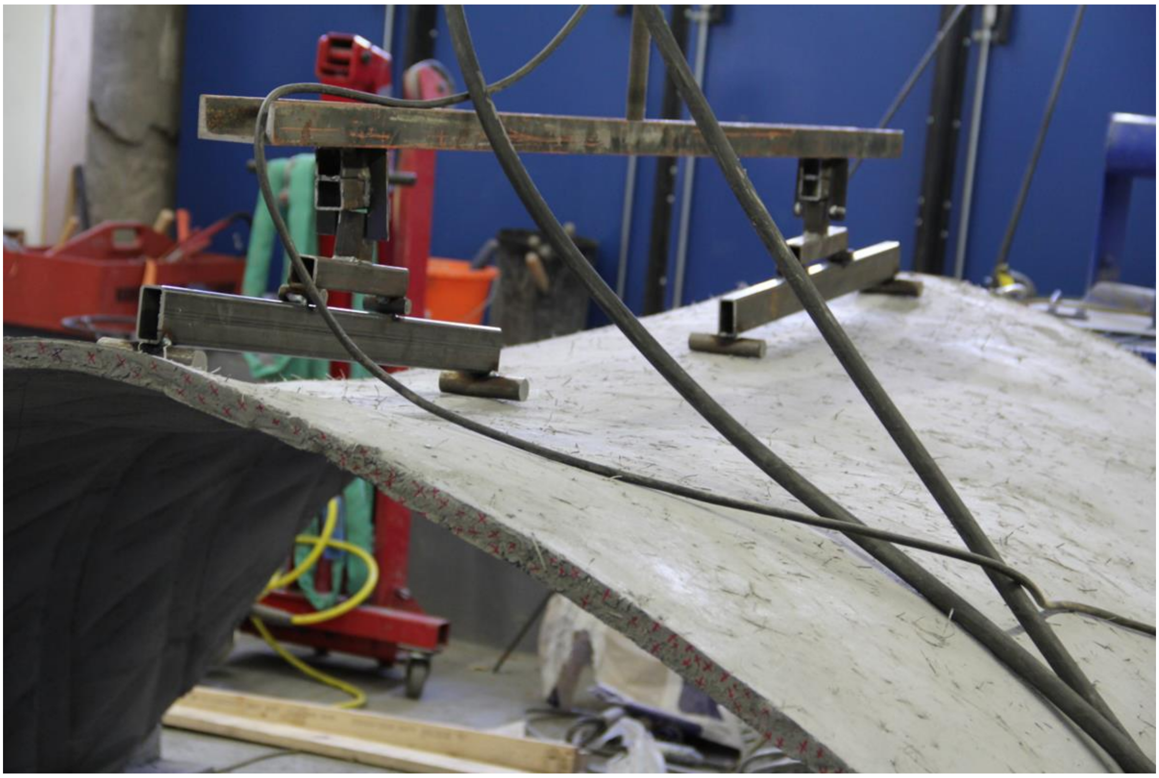


Fig 8.40 The load spreader transmits loads across the top apex of the shell.

Fig 8.41 Major implosion at the apex of the concrete shell.

Fig 8.42 The abutment was pried out of the ground.

Fig 8.43 Failure positions

Fig 8.44 The failure sequence

8.8 Conclusion

The test shell 3 constructions showed that a simple double-curved shell could be created with straight abutments using bracing elements that could be compressed or tensioned to induce a change of geometry in the gridshell and subsequently the concrete shell that is cast on top.

This construction exercise proved the possibility of creating double curved shells with straight length abutments. Gridshell material is an important choice. Flat mild steel sheets guillotined into thin strips and riveted together may not have been the ideal method of creating a deployable mat because:

- Firstly, the rivets were tight preventing the grid laths from completely rotating freely.
- Secondly, the mild steel was easily bent and deformed permanently.
- Thirdly, the material arrangement with sharp edges was not the safest to handle.

Therefore, metal strips may be used as sacrificial formwork but may not be practical for re-use. These resulted in a formwork that was dangerous to handle and difficult to work with. As the gridshell material could not twist easily, it resisted double-curved deformation crucial in giving concrete shells added strength. The gridshell was difficult to de-centre taking 100 minutes compared to 10 minute decentring for shell 1 and shell 2 respectively. Temporary props (i.e. timber propos) were necessary and useful to keep key points in check.

Due to the use of metal gridshell, the resultant concrete shell was flat and had shallow cushions with a thickness variation to span ratio of 0.67% as compared to 4% for Shells 1 and 2 respectively. The use of 20mm guides was useful to produce a shell with an even appearance seen from the upper-side. Following failure test, parts of the shell were measured and recorded thickest cushions near the abutments measuring 40mm.

Cushions are shallower with a smaller variation of 20mm compared to previous test shells. By using a viscous concrete mix, this required less “pressing in” of concrete to result in deep cushions. The result of the aesthetic of the shell bears direct relationship to the consideration for construction, clearly demonstrating the stereogeneous nature (Manelius, 2012) of this construction method.

Abutments are important considerations of designing concrete shells as they transfer loads effectively onto the floor. These cracks, restrained by the abutments and governed by self-weight encouraged the shell to fall inwards, rather than outwards.

Failure cracks are independent of the gridshell indent lines this case. It does not imply that deepest indent lines are the weakest and therefore most susceptible to cracks. The small failure load is attributed to pre-testing cracks as a result of the invasive de-centring process. This highlights the importance of a suitable gridshell system.

The following chapter explores GFRP (glass fibre reinforced polymer) as a possible gridshell material to address decentring issues and its behaviour to create complex geometries, as well as openings through doubly-curved shells.

Detail, Test Shell 1, 2014 (Gabriel Tang)

PART 3 CONSTRUCTION AND TESTING

Chapter 9

A NEW TECTONIC: COMPLEX CURVATURE, EDGE DETAILS AND OPENINGS

Chapter 9: A new tectonic

Shell 4: Complex curvature, Edge Details and Openings: Final Construction

The chapter concentrates on the elements of the technology to include investigating the creation of complex curvature in both formwork and concrete shell, the making of a flared edge and thirdly, the design and construction of openings in shells. These ideas are explored and discussed through carrying out the design, construction and eventual testing of a concrete shell with these design elements.

9.1 Aims

The aims of this experimental build further refines form and double curvature under three ambitions to demonstrate:

1. Complex curvature through use of glass fibre reinforced polymer gridshell.
2. The creation of free edges that did not extend to the edges of the gridshell formwork and
3. Openings in concrete shells.

9.1.1 Complex curvatures

The previous shells illustrate single curvatures (test shells 1 and 2). Test shell 3 was an attempt to achieve a double curved shell. This test construction attempts to create a shell with pronounced geometry change from anticlasticity to synclasticity and vice versa by creating an upturned edge detail.

9.1.2 Free edges

Fig. 9.1 Shell thinness expressed by a skilfull pulling back of stiffening ribs from the edges at The Barcardi Rum Factory 1960.

The artful design of the free edges to maintain that expression of filigree is perfected by Candela in 1960 where through gaining confidence and experience from previous shell constructions, he pulled back the stiffening edges (reinforced raised concrete sections visible in fig. 9.1) to maintain the visual impression of shell thinness of the edges. This was a vast improvement from the shells that he built at the earlier stages of his career seen in the fig 9.2 and fig 9.3. In the Bolsa de Valores (1955) expressed the stiffening edges on the outer edge giving these shells an impression of solidity and heft, as opposed to thinness and lightness. Although this aesthetic might have been intentional, the conscious effort to refine shell thinness as desirable aesthetic was perfected from a fundamental understanding of structural function and visual expression (see fig. 9.1).

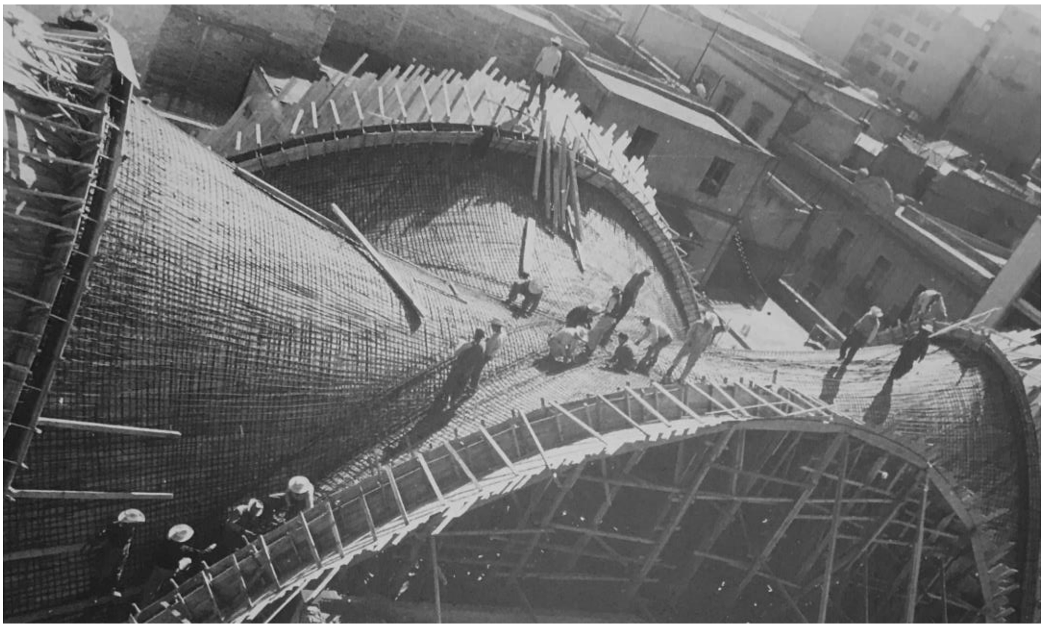


Fig. 9.2 Timber formwork and steel reinforcement visible in the Bolsa de Valores, Mexico City 1955.

Fig. 9.3 Edges were designed to appear solid and less plastic.

9.1.3 Openings

Shell designers have used some devices to introduce light and connection between the internal space and the external space. As discussed in chapter 3.3.8, Candela frequently used glazed gaps between his hy-par shells to allow light to illuminate shell interiors.

Fig 9.4 San Antonio del Huertas, Mexico City : Composed of a row of three groined hy-pars, the gaps between these are glazed to allow light to colour the spaces within.

Candela also used other means of introducing light into these often deep planned factory buildings by tilting his hypar umbrellas so that these umbrellas are tilted at an angle and allowed the light to pour into the spaces beneath. As well as tilting the hy-par parasols, he also used glass bricks to allow light to enter the spaces that it covered as illustrated in the High Life Textile Factory in fig. 9.5.

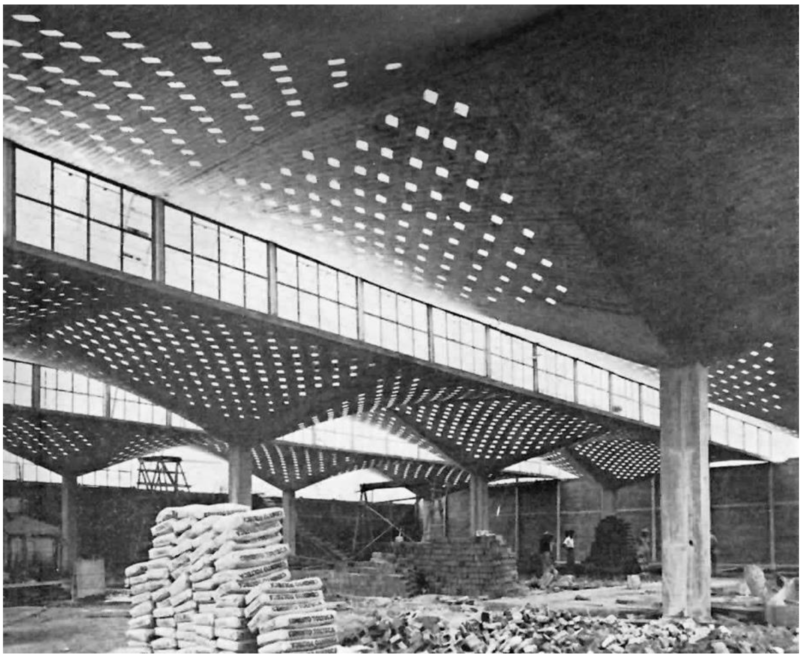


Fig 9.5 High Life Textile Factory, 1954-1955 Mexico City.

An alternative is to glaze front openings of the shells like the Los Mantiales in Xochimilco (1958). The latter gives a different quality of light which is often back-lit (fig. 9.6).

Fig 9.6 Backlighting and silhouette of side lighting at the Xochimilco shell, 1958.

To overcome this, designers have punctured holes through the concrete to allow light and air to enter the building. This introduces top light to deep-plans of shells. They can also be used to ventilate the spaces below. This is especially useful in a deep plan shell.

Isler created openings in many of his shells. In his bubble shell series, the middle was frequently punctured with a circular opening, usually detailed with an upstand that prevented water ingress and supported plastic domes. Also, many of his inverted membrane shells such as the Sicli shells also held numerous circular occuli. Some of the openings were open to the elements whilst others were topped with plastic dome roofs to thermally seal off the internal spaces.

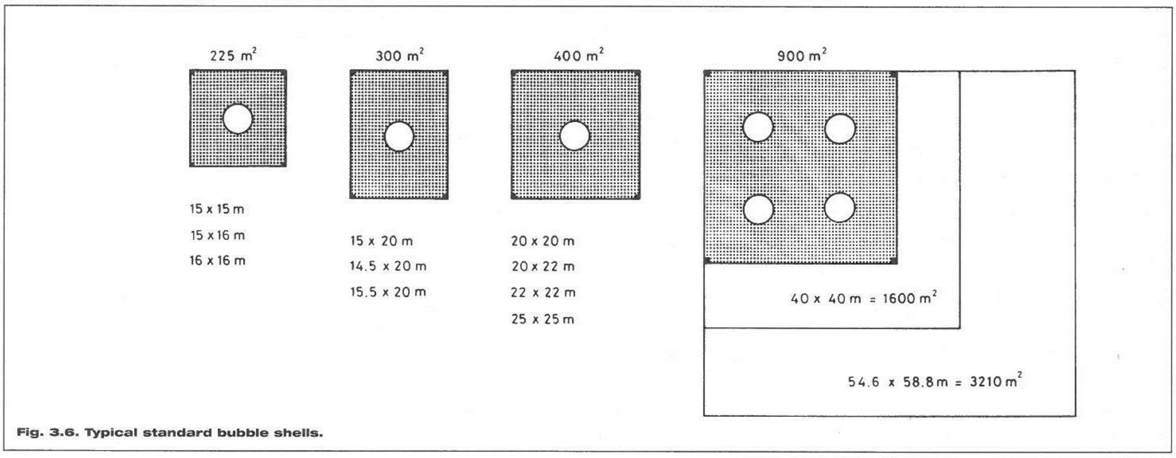


Fig 9.7 One of the bubble shell series (From Chilton, 2000)

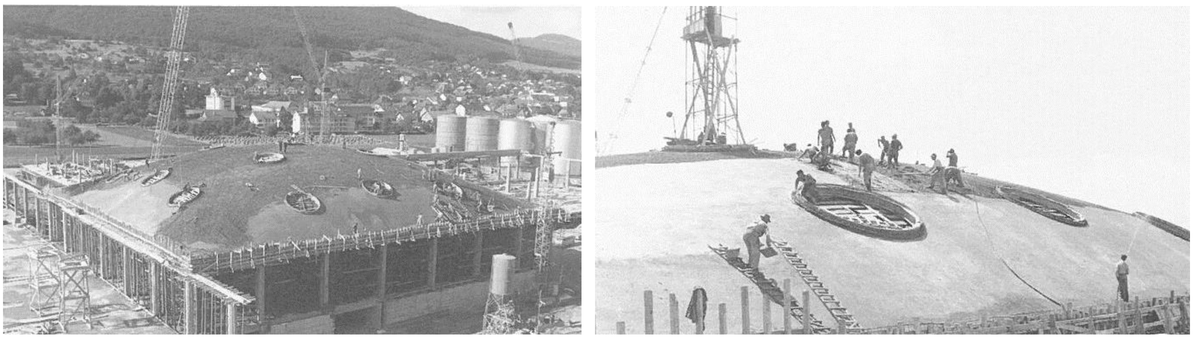


Fig 9.8 One of the bubble shell series (From Chilton, 2000)

Fig 9.8 shows one of the bubble shell series, the concrete shell has circular openings with upstands and is covered by a plastic dome window to allow light to penetrate into the deep planned spaces under the shell. The Sicli shell, an inverted membrane shell completed in 1969, has a series of circular openings. The main opening measured 6 metre in diameter. (http://www.heimatschutz.ch/GE-Geneve-Usine-Sicli.613.0.html).

Fig 9.9 The Sicli shell with oculus windows. Some of these openings are covered with a domed plastic windows at present day (From Chilton, 2000)

- Openings in the shell surface were also achieved by Eladio Dieste. Seen in the openings through the doubly-curved roof of the Church of Atlantida, a series of cylindrical terra cotta openings punctured masonry shell roof. As the shell was composed of thin brick tiles, the principles of making the windows were straightforward. The tiles were removed and terra cotta inset rings were used to create openings that brought light into the space.

fig 9.10: Six small and one larger terra cotta cylinders penetrates through the masonry shell roof to bring light into the interior church space.

fig 9.11 details of terra cotta cylindrical windows.

Fig 9.12 top : Interior of a brick vaulted salt silo at Montevideo by Eladio Dieste. Bottom: the exterior of the salt silo is cemented with a thin layer of mortar and the strip windows glazed with plastic windows.

The above example fig 9.12 shows a salt silo in Montevideo by Eladio Dieste shows another way of introducing working level light into the space within. In this example, openings were created by removing parallel rows of brick tiles from the shell and did not disturb force flows to the ground. Again, structural understanding is integral to the shells of Eladio Dieste.

In previous test shell builds, concrete shells cast from deployable gridshells express formwork clearly through early experiments by the imprints of the gridshell formwork. Stereogeneous to the process of construction, part of the research questions how these openings through these concrete surfaces should be designed and appear. The answer in this method might be governed by the grid patterns. It is envisaged that for practicality and to respect the aesthetic of the shell, openings may be treated as removing concrete material from the shell such that forces are concentrated on the geodesic lines suggested by the gridshell formwork underneath.

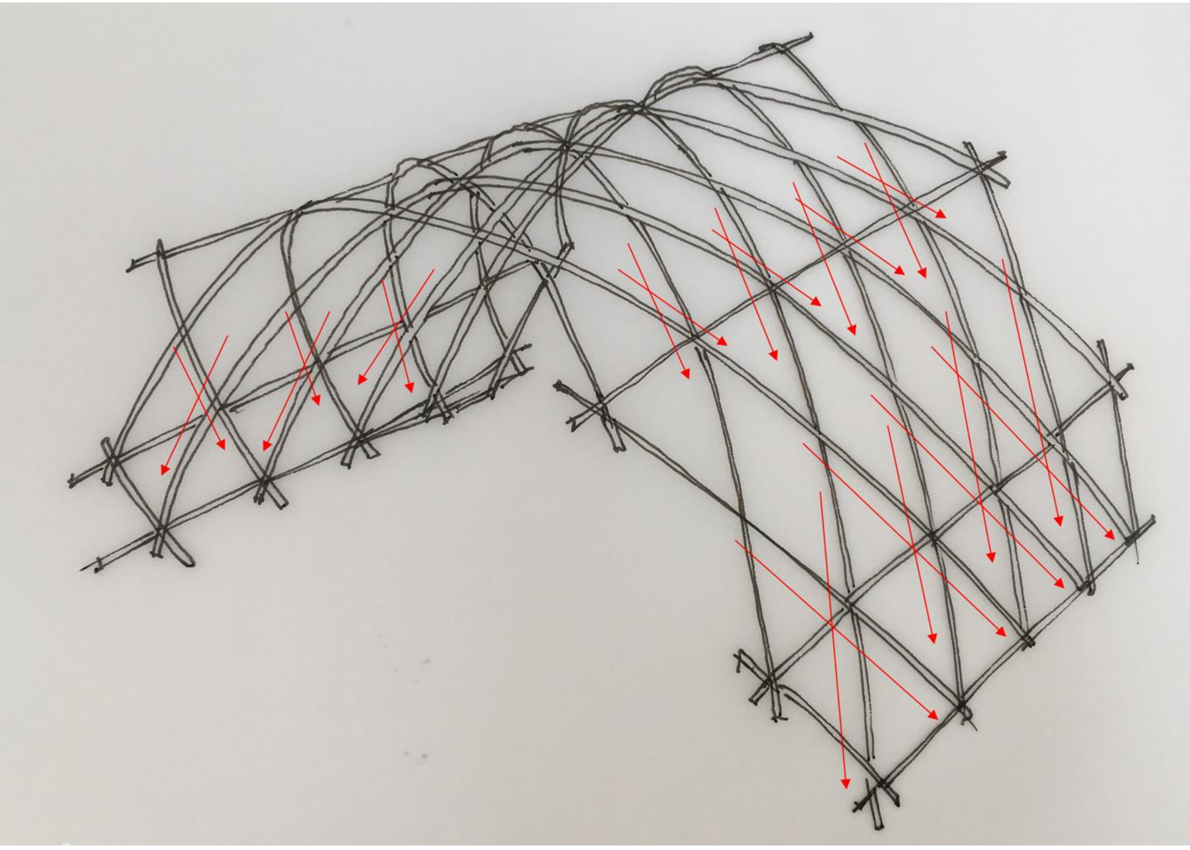


Fig 9.13 Forces of the gridshell are concentrated on the gridlaths and travel within these strips.

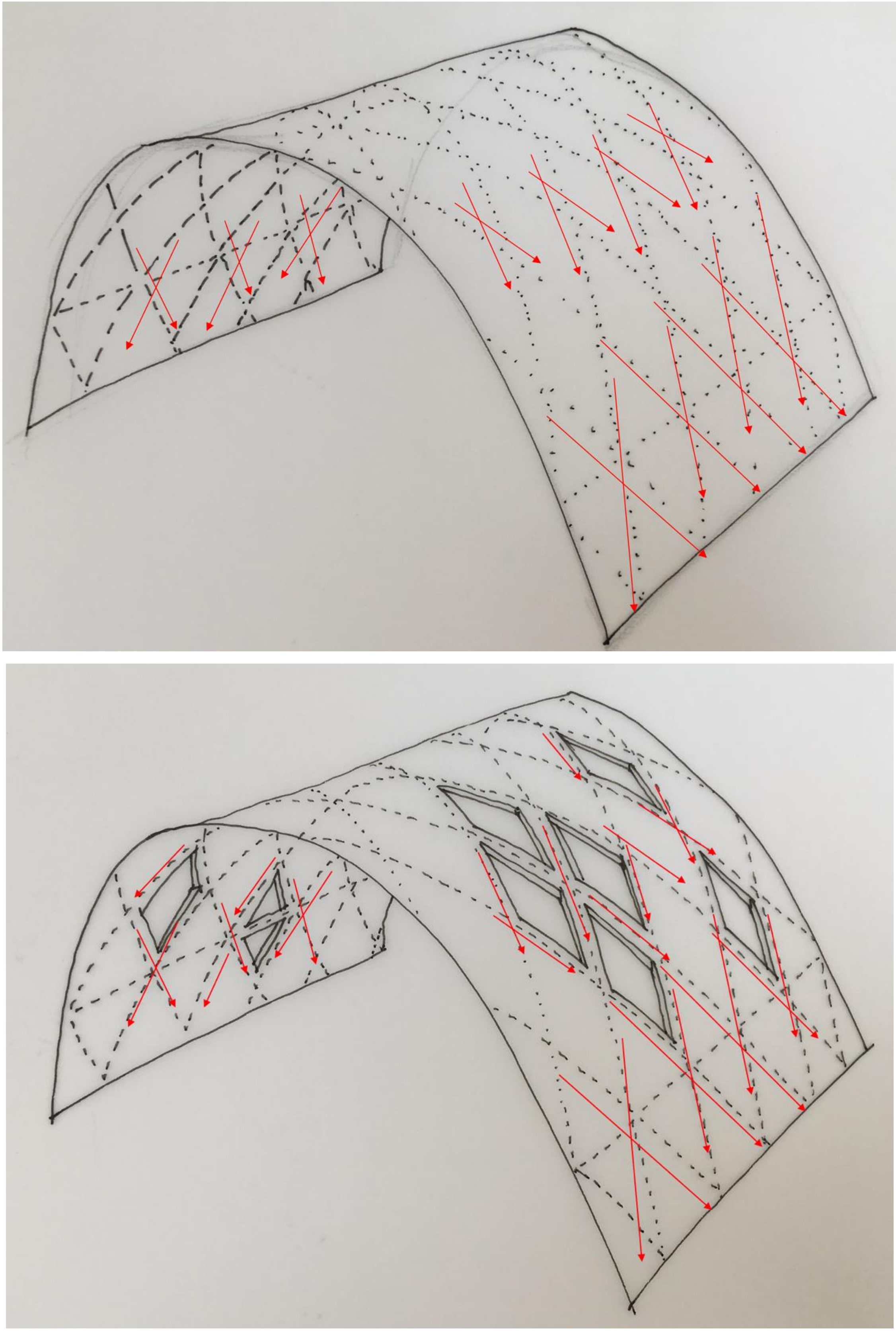


Fig 9.14 Top: On a concrete shell cast over a gridshell formwork, forces travel through the concrete shell in the same directions as the gridshell indentations. The dominant lines create deeper cushions in a single direction of the shell and may have an impact on buckling capacity. Bottom: Openings can be made in the spaces between the gridlines. Force lines flows around the openings as illustrated

9.1.4 GFRP (Glass Fibre Reinforced Polymer) for gridshell

The previous test showed that metal sheets may not be the most suitable material for creating gridshell formworks. Carbon fibre tubes and glass fibre reinforced plastic replaced timber with high elastic modulus stable in external environments. Unlike timber, carbon fibre tubes and GFRP tubes do not contain knots and are consistent in elasticity, therefore these man-made materials are controllable, making them attractive to be used as material for gridshells. They are also water-resistant, making them suitable for use during concrete casting.

Therefore, glass fibre reinforced plastic (GFRP) tubes have attractive structural qualities to this application. Not only do they possess high elastic modulus, they return to their original positions easily (Kotelnikova-Weiler et al. 2013). Hollow GFRP tubes have been used structurally in a number of temporary gridshell pavilions covered with a continuous waterproof membrane carried out by the research groups led by O Baveral and C Gangnagel.

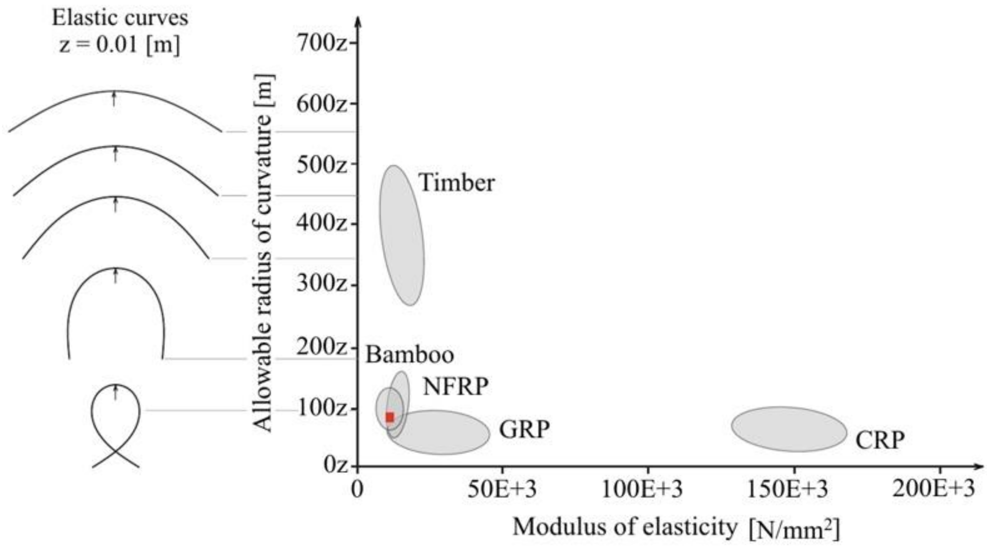


Fig 9.15. Material properties with respect to active bending. The graph shows GRP (glass-fibre reinforced plastic) having both high bending-strength/ Young's modulus ratio with very high flexibility to create elastic curves. CRP (Carbon-fivre reinforced plastics) (from Gangnagel, Lafuente Hernandez and Baumer, 2010)

In 2011, and 2012, the Solidays pavilion and the Creteil Church (Bavarel, 2012) were constructed by connecting tubular lengths of GFRP tubes together using special clamps. The Creteil Church, measured 350 m2, was first laid out flat in the ground before being lifted by cranes. (Peloux, Tayeb, Caron, Baverel, 2015). The actively-bent gridshells had lightness and flexibility. This was also made possible due to the double swivelling joints temporarily securing crossing laths, but which allowed rotational freedom. These loose joints secured together by wires, rather than nuts and bolts swivelled to accommodate torsion.

Fig 9.16. Cretail Composite gridshell created in 2012 was created from GFRP tubes connected by special swivelling joints. (Peloux, Tayeb, Caron, Baverel, 2012)

9.2 Test

Test shell 4 was designed and built to explore openings, free edges and complex geometries.

9.2.1 Test Materials

Formwork

- 30 no. 3m lengths of GFRP tubes 8mm diameter with 1.5mm walls were used. 2mm diameter holes were drilled through the tubes at a distance of 200mm to allow them to be tied together with
- 0.5mm guage wires. They were laid in a criss-cross manner as illustrated in the figure below and the wire was threaded through and twisted through to create a deployable gridmat.
- Pvc conduits 10 x 16mm hollow pipes for bracing and forming edge details.
- 18mm thick baseboard measuring 1800mm x 900mm
- 50mm x 50mm softwood timber members screwed to plywood baseboard to form abutments channels

Concrete

- 62.5kg sand,
- 25kg cement,
- 150g 40mm Strux 90/40 Synthetic Macro Fibre plastic reinforcement
- 14 x 600ml water
- cotton fabric

- cotton sewing thread to stitch fabric to gridshell
- mdf blocks and screws for making resist “impactos” (West, 2016 and Manelius, 2012) for creating openings.

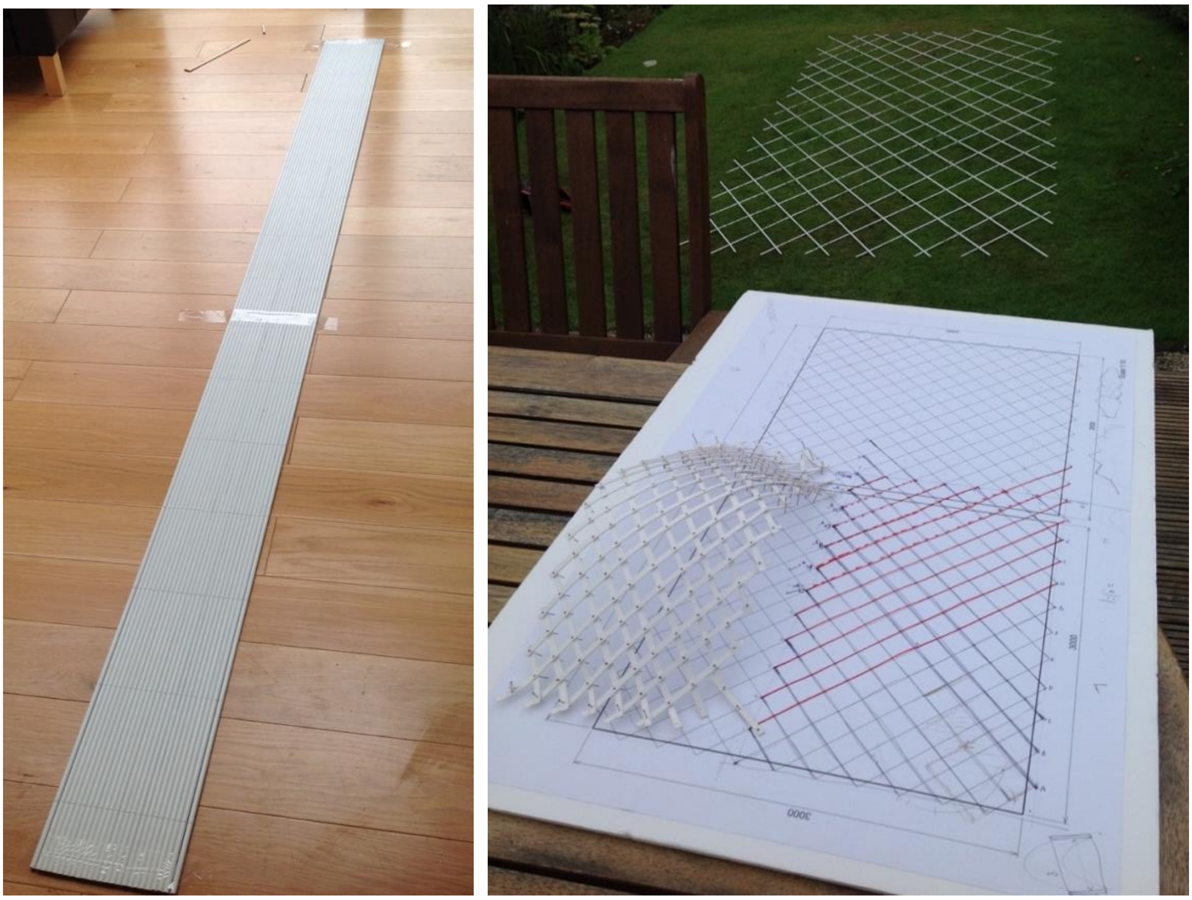


Figure 9.17 The 3m long GFRP hollow tubes were marked and drilled with 2mm diameter holes to pass a 1.5mm diameter wire through and tied together to form a deployable gridmat.

Figure 9.18 The laths are tied together with steel wires.

The glass-fibre tubes were attached together and the location of holes for drilling marked. They were then laid out to create a gridmat that measured 2m by 3m on plan. 2mm holes were drilled at each location.

Compared to earlier gridshells, this gridmat felt stronger and stiffer yet more flexible and easier to manipulate resulting in a variety of shape possibilities.

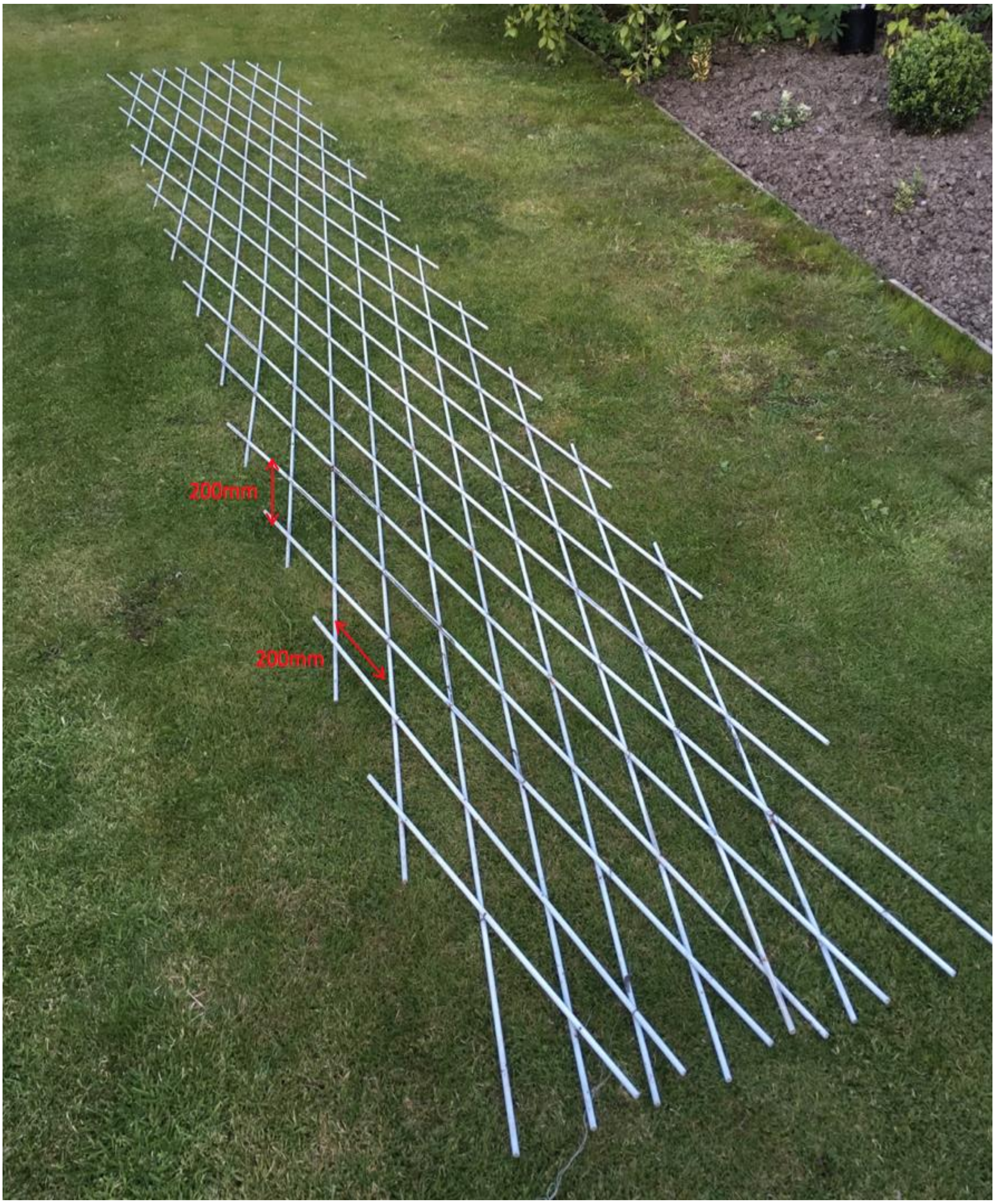


Fig 9.19 Grid dimensions

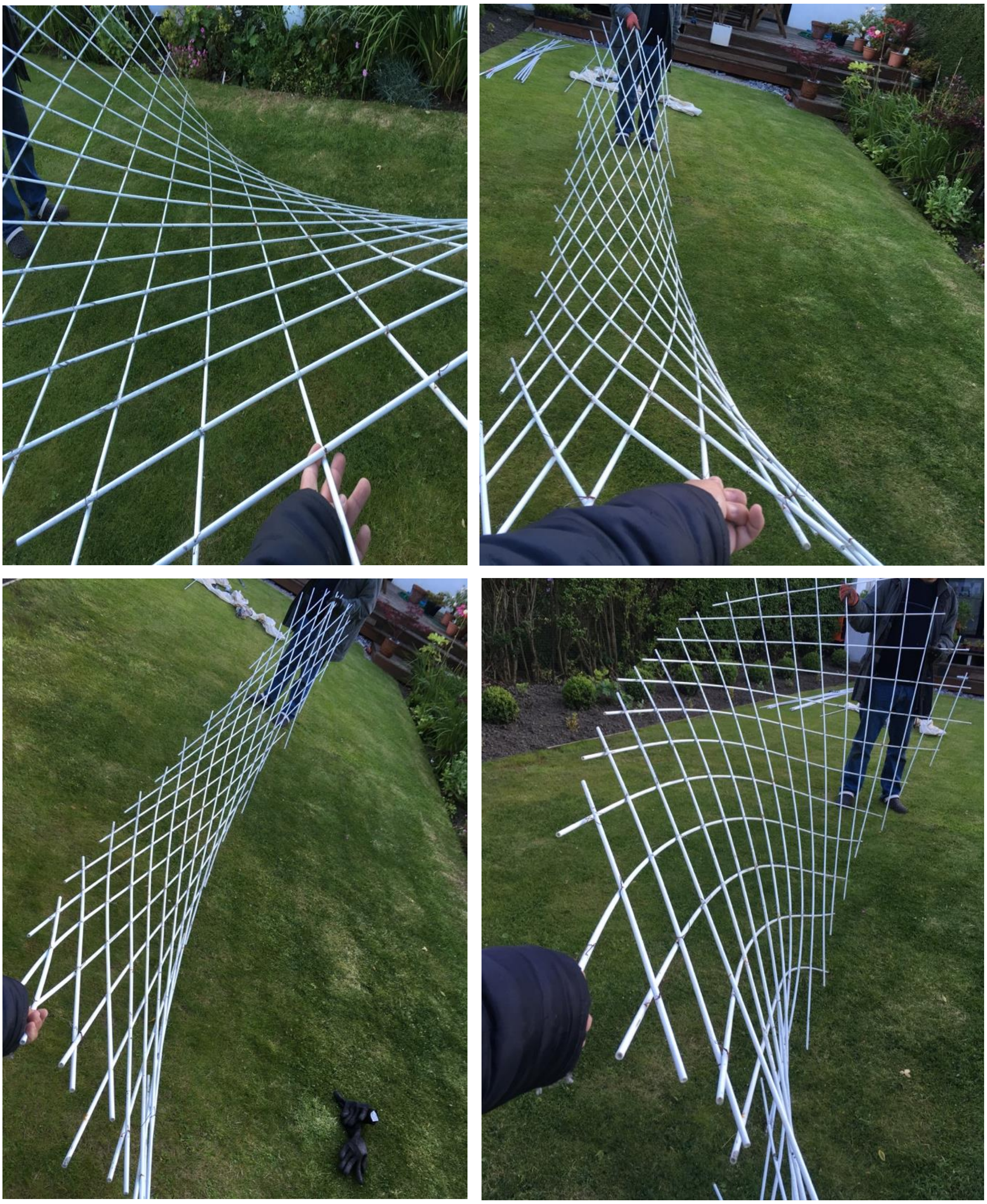


Figure 9.20 shows the various shape possibilities when manipulating the gridmat with a variety of shaping including the distinctive hypars resulting in a variety of concrete shell casting possibilities. The gridmat is flexible and easily deployed.

9.2.2 Simplifying the abutments

To create the shell, the partially stabilised gridmat was propped between abutments formwork by screwing timber planks onto a 18mm thick baseboard measuring 1800mm x 900mm on plan. To stabilise and prevent the gridmat from reverting back to the flat mat, pvc conduit tubes with elliptical section measuring 16mm x 10mm were fastened at the ends. Compared to GFRP tubes, pvc trunking was cheap to buy (£0.12 + VAT/ m from www.bes.co.uk/) and it was also very easy to drill. As such, they were chosen for their ease of workability, lightness and cost.

The GFRP tubes were tied together with 1 mm steel wire passing through each element and twisted together to form a rotating yet secure joint. To ensure the gridshell was securely attached to the base and abutment, the structure was tied using steel cables to screws attached to the bases as shown in figure 9.20.

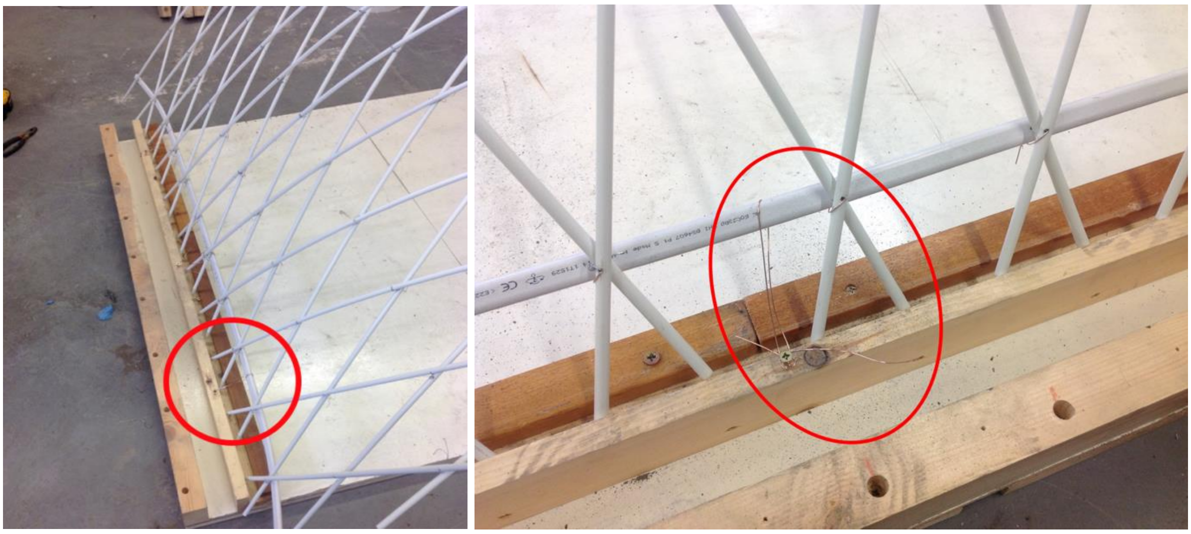


Fig 9.21 Metal wires were used to tie and attach the gridshell back to the abutments to prevent the formwork from springing off and detaching from the abutments.

The abutment design is a further simplification of the previous pre-cast concrete abutment use. In this design, concrete is poured within the space between timber planks to form an abutment connecting physically to the shell as one monolithic entity. This eliminates the step of casting a pair of concrete abutments, thereby streamlining the construction stage.

9.2.3 Gridshell as a Self-adjusting formwork

Described in fig 9.21 above, the shell was first braced at the line nearest the abutments. The entire shell readjusted to form a dome at the apex. It was observed that the edges of the shell had a tendency to turn upwards and outwards (fig. 9.23). Therefore, the actively-bent formwork self-adjusts intuitively to fit into the straight bases. This responsive behaviour of formwork compared to similar gridmats of previous materials made GFRP attractive to achieve the desired complex double curvatures.

Figure 9.22 GFRP Gridshell actively bent and in position

Figure 9.23 Pushing and pulling gridlaths enhance the shell shape

After the gridshell was positioned in place, to build up double curvatures, learning from the pre-test mock-ups for test 3, the central mid-span area was pushed out and apart to create double curvatures especially pronounced at the apex. PVC hollow conduit pipes were used to brace the structure and induce this geometry. They were chosen over GFRP for their lightness, cost economy and ease to drill. As these were used and discarded afterwards, it is unnecessary to use costly sections of GFRP hollow tubes which are also difficult to drill. The pvc tubes cost £0.12/m + vat whilst a gfrp hollow tube 8mm with 1.5mm walls cost £8.95 + VAT (https://www.ecfibreglasssupplies.co.uk) making it almost 75 times more expensive. This geometry is reminiscent of Heinz Isler's Wyss Garden Center in Solothurn, Solothurn, Switzerland(1961), which introduced an up-turn detail which also acted as an arch beam (Chilton, 2000).

Fig 9.24 Wyss garden centre with upturned edges. (www.wikicommons.com)

Next, additional pvc conduit tubes were attached to brace the structure across quarter spans. By using these conduits as bracing, the grids could be pulled together or pushed apart to further adjust the geometry of the gridshell and make the geometry more or less pronounced. Compared to test shells 1, 2 and 3, double curvatures were visibly more pronounced once the pvc bracing sections were attached. In this case, the bracing system for the structure was used more than just provide in-plane rigidity, it was also used to manipulate curvatures pre-stressing the entire gridshell surface. This ability means that double curvatures beneficial to shell stability could be controlled.

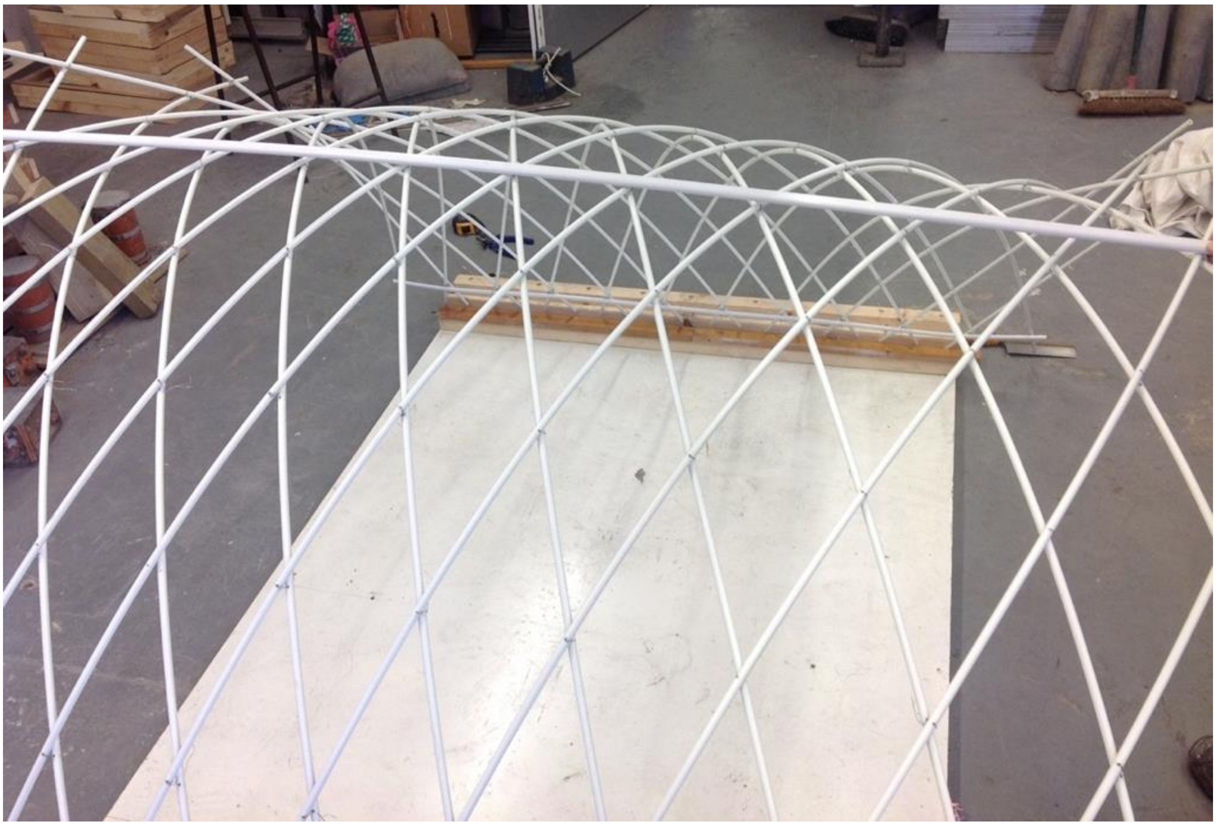


Fig 9.25 The PVC apex lath was attached across the shell to stabilize the structure. However, to accentuate and maximize double curvatures, diagrids were pushed apart in this area to induce distinct double curvatures.

In fact, a similar situation was observed in the triple bulb formation of the Jerwood timber gridshell at Weald and Downland Open-air Museum where project carpenters experienced difficulties in creating double-curved geometries at the “waists” and valleys. This was resolved by pulling the grids at strategic areas by attaching ratchet straps and tightening ratchet straps attached to pre-determined grids (Harris et al, 2003). The structure was much more responsive to forces applied to the grids.

9.2.4 Edge Definition

Edges of the shell were defined and strengthened by attaching two pvc conduits pipes, one laid above another and tied together using steel wires to form a “tray” detail similar to test shell 1 and 2. After fabric was laid across the formwork, concrete was applied atop to create a sharply defined splaying free edge. The edge followed the diagonal grid lines with the intention to cast a concrete shell with edges that leant outwards to demonstrate the possibility of creating expressive shells.

The edges developed the desired double curvatures. Pulling and pushing the gridmat caused the shell to change its geometry. The grid mat pattern was imprinted on the underside of the shell.

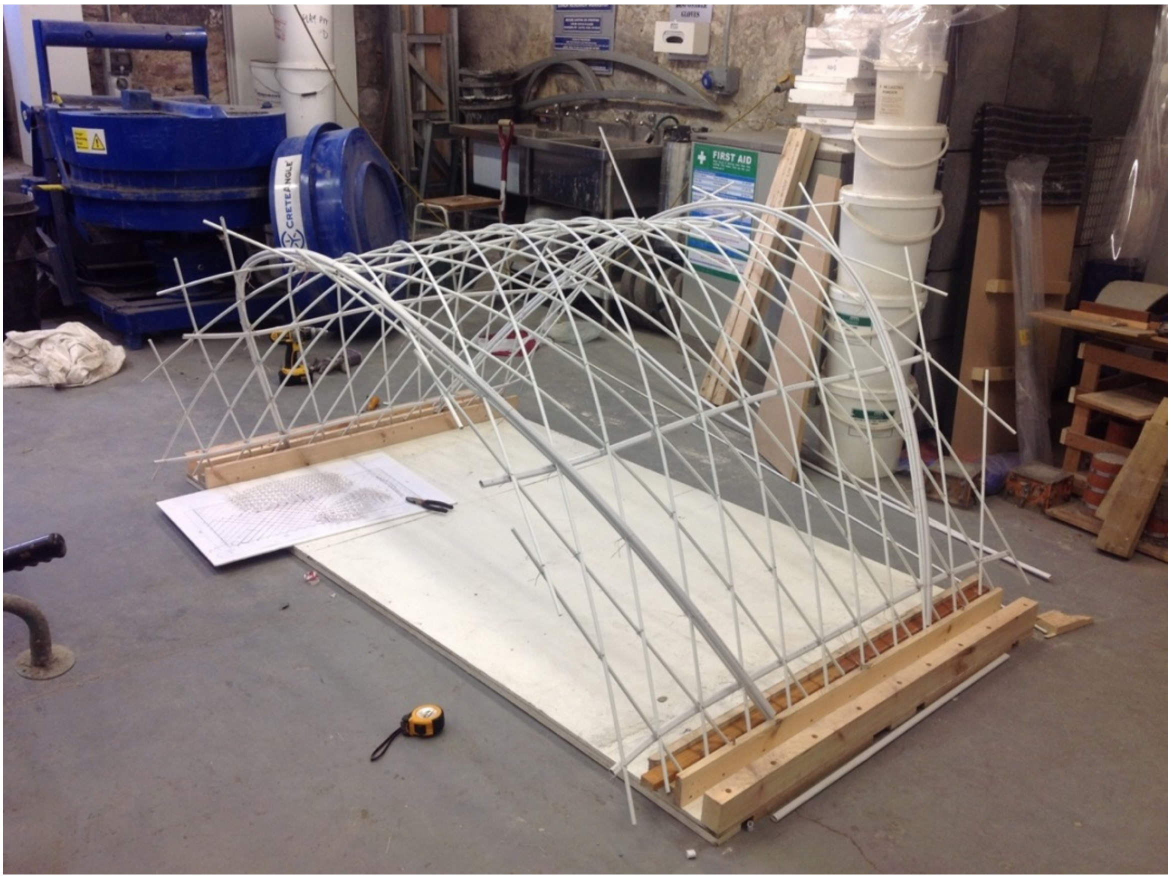


Figure 9.26 Edges installed

Fig. 9.27 By pushing together or pulling gridmat apart at the apex, the gridshell morphology could be controlled to introduce stiffness and strength.

9.2.5 Openings

Respecting the gridmat, diamond shape openings were installed in the concrete shell.

To do this, the entire shell was covered with fabric where concrete would be applied. A smooth gauge cotton cloth measuring 3m x 3m was draped over the gridshell formwork shown in the fig. 9.28. It was subsequently pulled tightly to stretch the fabric over the gridshell to avoid wrinkling or pleats as these may cause additional sagging and a wrinkled surface finish. The fabric was then sewn and hemmed around the pvc trunking edge beams to create a smooth surface (without any wrinkles) onto which concrete was applied. The GFRP formwork was noticeably stiffer than previous shells.

Figure 9.28 preparing the gridshell formwork.

The fabric formwork clearly hinted the upper layers of grid lines running in one direction illustrated in fig. 9.28. Again, the layering of laths influences the appearance of cushion patterns that appear on shell underside. The appearance of protruding grid laths was inscribed onto the under-surface of the eventual concrete shell. Excess fabric was trimmed away to prevent surplus material from being trapped within the concrete cast. Care was taken to ensure no surplus fabric was left inside the channel for the concrete abutments. As discussed earlier in chapter 9.1.3, the interiors of concrete shells suffer from a lack of top lit natural light. As shells are efficient in spanning and covering large areas, potentially producing deep planned buildings, the incorporation of openings brings natural light and fresh air into the spaces below.

Aesthetically, the diagrid/ diamond shapes of the gridmat inspired the opening with respect to this pattern language. To create these openings, the openings are made from mdf blocks attached onto the fabric formwork to mask concrete and form openings suggestive of windows or skylights in a live size concrete shell. Each lenticular "resist impacto" (coined from *impactos* used by West (2016), Pedreschi and Chandler, 2007) and Manelius (2012)) was formed by sandwiching triangular blocks and wrapped in plastic cling film to ensure it could be removed easily when concrete was cured. The composite lenticular blocks also had intentionally rounded corners for ease of removal. These were then attached onto the fabric formwork by nuts and bolts to allow these to be removed easily afterwards and not become trapped in the concrete shell. The ease and effectiveness of removing the resist impactos from the concrete is paramount.

9.3 Construction

9.3.1 Formwork Movement during casting

When fabric formwork preparation was complete, concrete was applied. To understand and check the movement of this gridshell, movement was recorded via plumb lines similar to the exercise for Shells 1 and 2. For this exercise, plumb lines were attached to the gridshell at three span locations – the midspan (i.e. apex), and quarter spans at both sides of the shell i.e. where the pvc hollow cross bracing tubes were located.

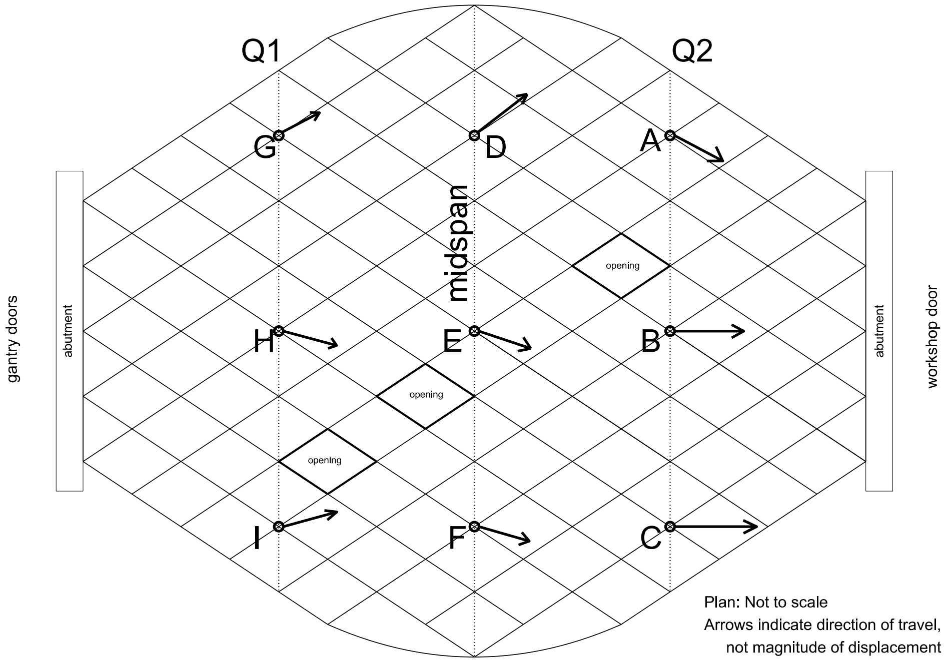


Fig. 9.29 shows the location of plumb lines.

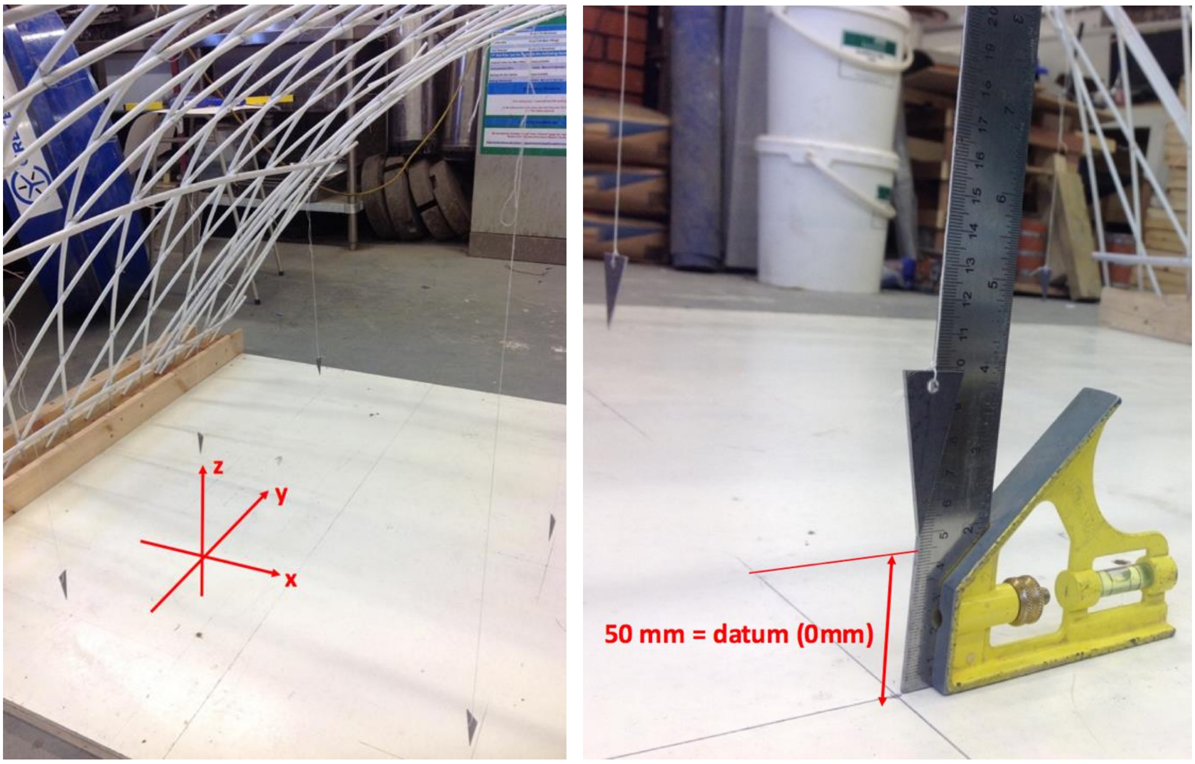


Fig. 9.30 Datum positions

Casting/ Gridshell Movement Analysis

Data below are positions of the plumb lines after casting. Starting positions of the points are measured from datum of 0,0,0.

Q1 (mm)	Mid-Span (mm)	Q2 (mm)
G (+50, +8, -7)	D (+55, +15, -38)	A (+70, -13, +27)
H (+55, -5, -7)	E (+42, -7, -13)	B (+50, 0, +23)
I (+56, +20, -8)	F (+47, -8, -25)	C (+70, 0, +26)

Figure 9.31 Movement Measurements

Similar to movement checks for test shells 1 and 2, plumb lines were set out 50mm above base level. A cross parallel to the edge of the base edge was drawn and used as the x-axis. The axis perpendicular to this axis was set as the Y axis with the vertical axis set the z-axis. When the concrete was completely applied, the final positions were measured to gain an understanding of how much the shell had moved during the casting process.

- Examining the x-axis for each point, the shell leant to the direction of Q2. Looking at the vertical axis (z-axis) figures, it appears that the shell has risen at the Q2 regions by an average of 25.3mm. At mid-span, these points have also moved in the direction of Q2 area. However, points E and F, moved in the same direction in the perpendicular axis by approximately the same amount of 7mm and 8mm respectively, whereas point D moved away from point E and F in the opposite direction by 15mm. It would suggest that the regions between E and F would develop flatness. The final positions of the points in mid-span have all been lowered by also an average of 25.3mm. At Q1 positions, all points G, H and I have moved towards the mid-span. In the y-axis, point I have moved 20mm towards point H, which has also moved 5mm closer to point H. This suggests a compression of the areas between these 2 points which beings about compression stresses in the gridshell.

- The new distances are an indication of the self-re adjustment and redistribution of stresses on the shell itself. They are directly linked to the concrete (deadweight) and the forces involved in applying the concrete – live loading.

- It is also noticed that all points at Q1 have experienced an approximate same amount of lowering of -7mm, -7mm and -8mm for points G, H and I respectively.

- In all four cases of constructed shells, the first region of concrete application determined the leaning/ deflection of the eventual concrete shell. The figures also showed that on the opposite sides, where the first concrete was deposited, the shell will experience a rise in height at the apex. The shell shape was highly dependent on the construction sequence. Quite unlike other forms of formwork, this system which utilizes fabric formwork is flexible and highly responsive to forces applied.

- The responsive self-adjusting nature is an attribute of the formwork. However, it has shown to be very uncontrollable at the time, resulting an unexpected change of dimension. To increase controllability, the grid shell could be stiffened with additional bracing, perhaps at every single intersection to produce a strong and stiff shell that was prone to deflecting whilst casting.

9.3.2 Concrete Mix

The concrete was mixed with the same consistency as test Shells 1 and 2. No steel reinforcements were used in the shell, but 20 mm polypropylene STRUX fibres were added in the first mix. The concrete mix consisted of:

62.5kg sand,
25kg cement,
150g 40mm Strux 90/40 Synthetic Macro Fibre plastic reinforcement
14 x 600ml water

Concrete was applied at two stages, the first coat of approx. 10mm, and a second coat approx. 10mm thick was applied next. The top coat which did not have any reinforcement rendered a completely smooth appearance.

9.3.3 Casting Sequence

The areas near the abutments were filled first. Concrete was applied to right hand section, then the left. Following that, concrete was applied from the top i.e. apex and then with firm strokes of the trowel, join the concrete to meet the earlier lower sections. The shell was left to achieve the right consistency for 20 minutes, and then the entire surface was smoothened. Throughout the casting process, the entire gridshell formwork was comparatively stiffer than other materials used. The forces used on the material did not affect the geometry of the shell. In total, the construction and casting took 3 people 12 hours altogether. Compared to PVC and metal gridshell, the GFRP material responded very well to the casting. No intermediate supports or props were installed in the construction of this concrete shell.

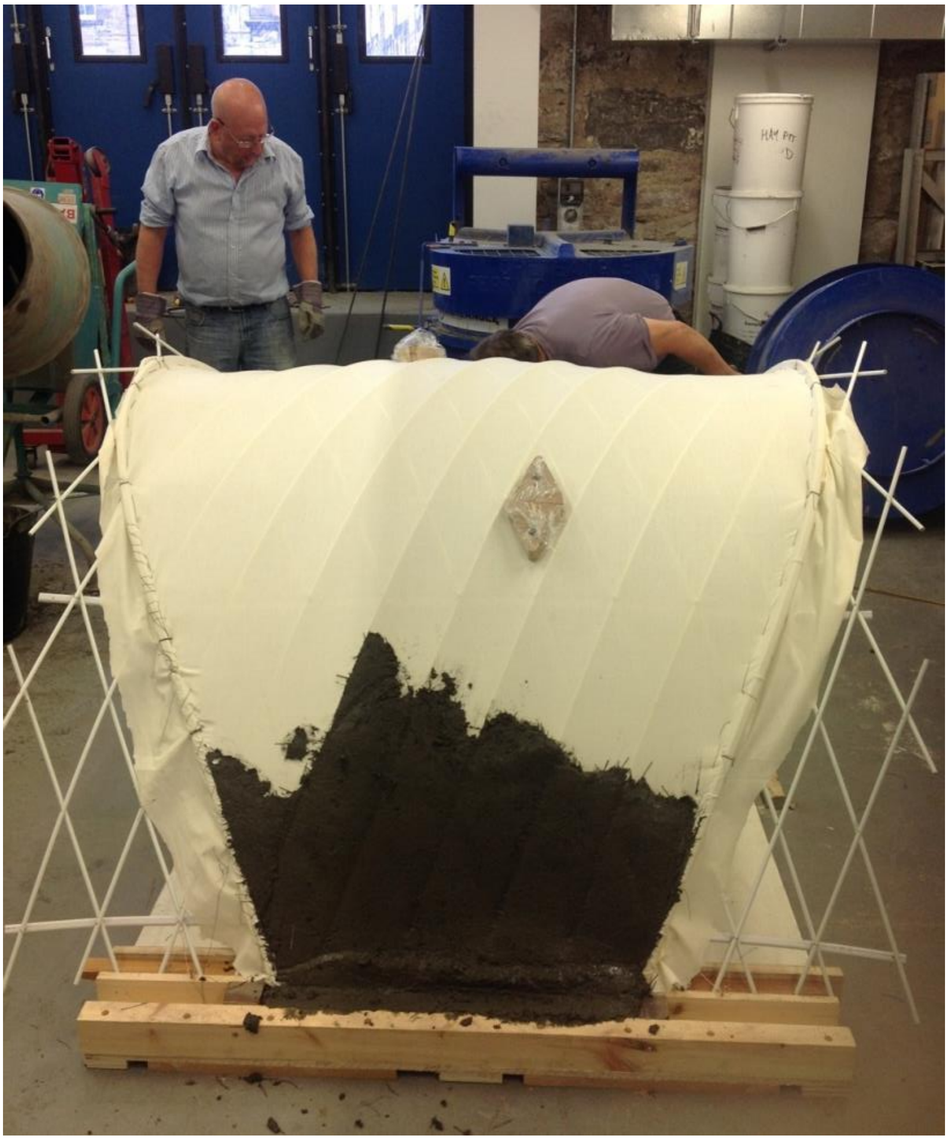


Fig 9.32 Areas near the abutments were cast first.

Fig 9.33 The first casting was left to cure to gain concrete stiffness.

The finished shell was then covered up under a tarpaulin to cure so as to prevent it from drying up too quickly as this will diminish the strength of the concrete. The concrete shell was left to cure for a period of 72 hours.

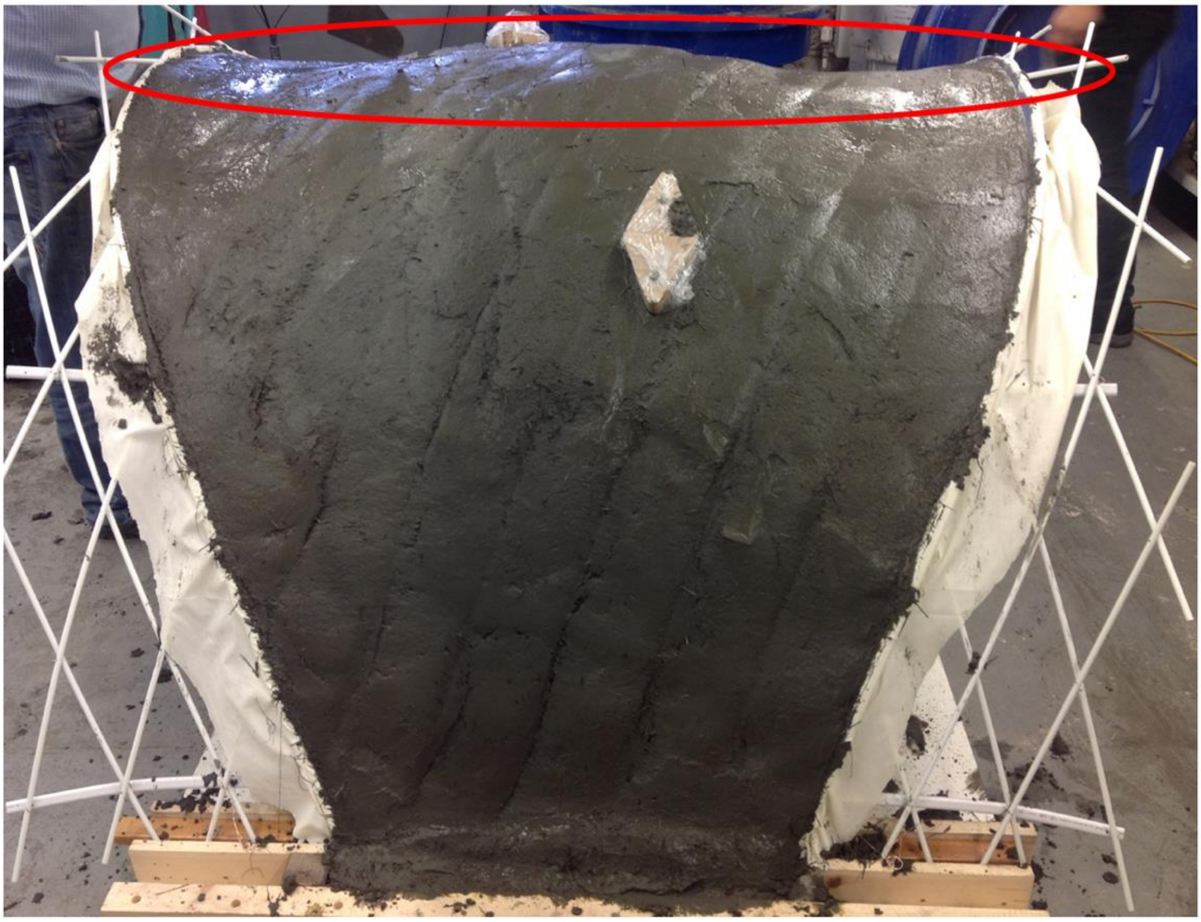


Fig. 9.34 The profile and double curvature of the shell was distinct and was visible in the profile cross section of this photographed view.

9.3.4 De-centring

Diagrid Openings

Formwork stripping commenced with the removal of the *resist impactos* that created the openings. With nuts and bolts quickly unfastened, the three blocks came apart and were removed from the concrete shell itself, leaving a diamond-shaped opening as designed.

Fig. 9.35 The resist impactos were screwed though the fabric and supported temporarily before concrete shell was cast.

Fig. 9.36 Once the concrete shell was cured, The resist impactos were detached easily

Fig. 9.37 Resist impactos were removed completely to form the shell opening.

Fig 9.38 Fabric adheres to the underside of the concrete shell once the gridshell was removed.

The next stage required all sewing and stitches to be removed. Pvc bracing tubes were next removed. As expected, when completed, the GFRP gridshell was released. The gridshell returned back to the rest position, folding back into a very compact bundle.

Fig. 9.39 a) above: the fine texture of the completed shell. B) below: the completed shell displaying pronounced double curvatures

The cotton fabric attached to the concrete shell was peeled away from the concrete shell to reveal the fresh concrete which borrowed the texture of the fine cotton weave. Compared to test shells 1 and 2, it was a finer concrete surface, much smoother than test shell 1 and 2 and with fewer blow holes. This might have been due to the smoothing of concrete on the under-surface of the concrete shell during the construction see fig. 9.39 (top).

The movement of the shell was recorded whilst concrete was applied and data was recorded. This is presented and discussed in detail in the next section.

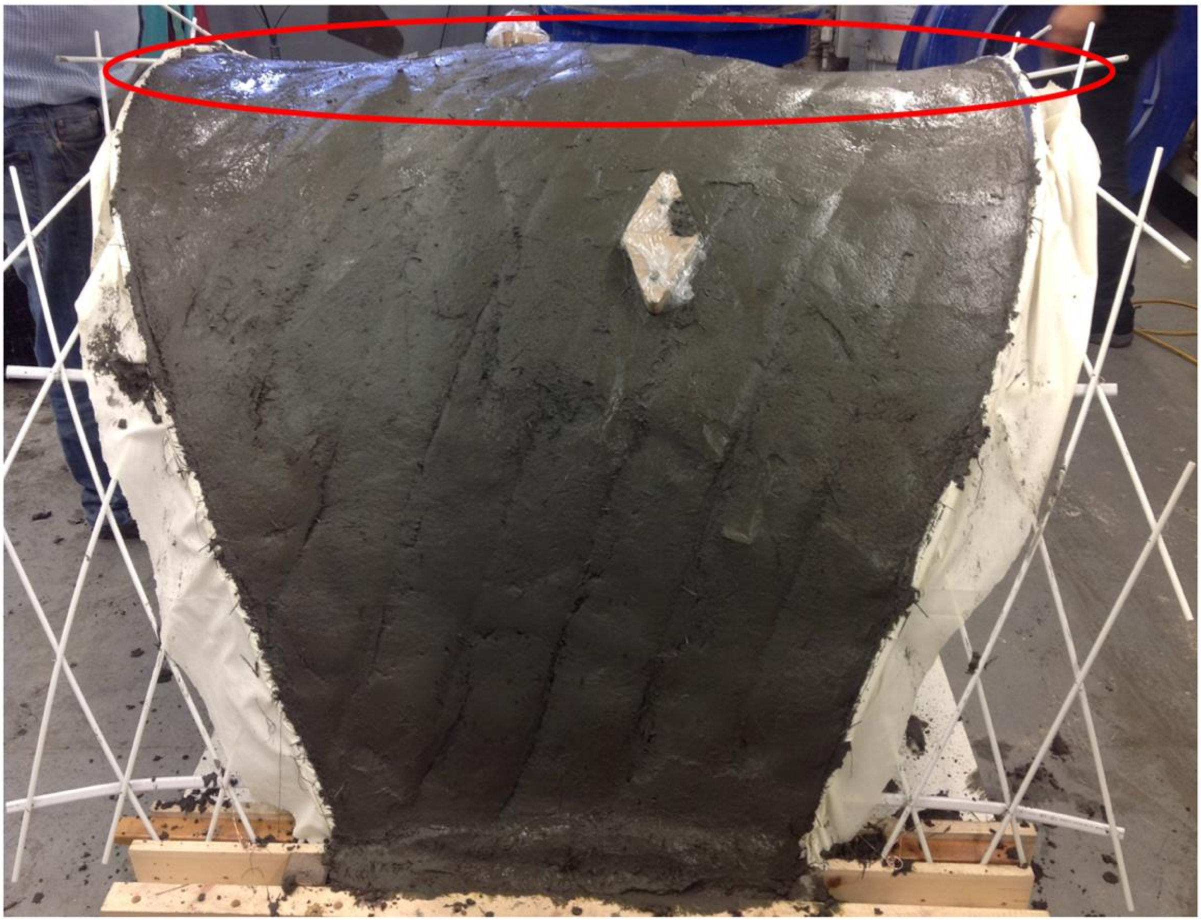


Fig. 9.40 The profile and double curvature of the shell was distinct and was visible in the profile cross section of this photographed view.

This concrete shell was constructed without struts or stabilizing support props. Also, no timber supports were used to support the bottom sections of shells near the abutments to prevent concrete from flowing into the gaps between the gridshell formwork as had to be done in test shells 1, 2 and 3.

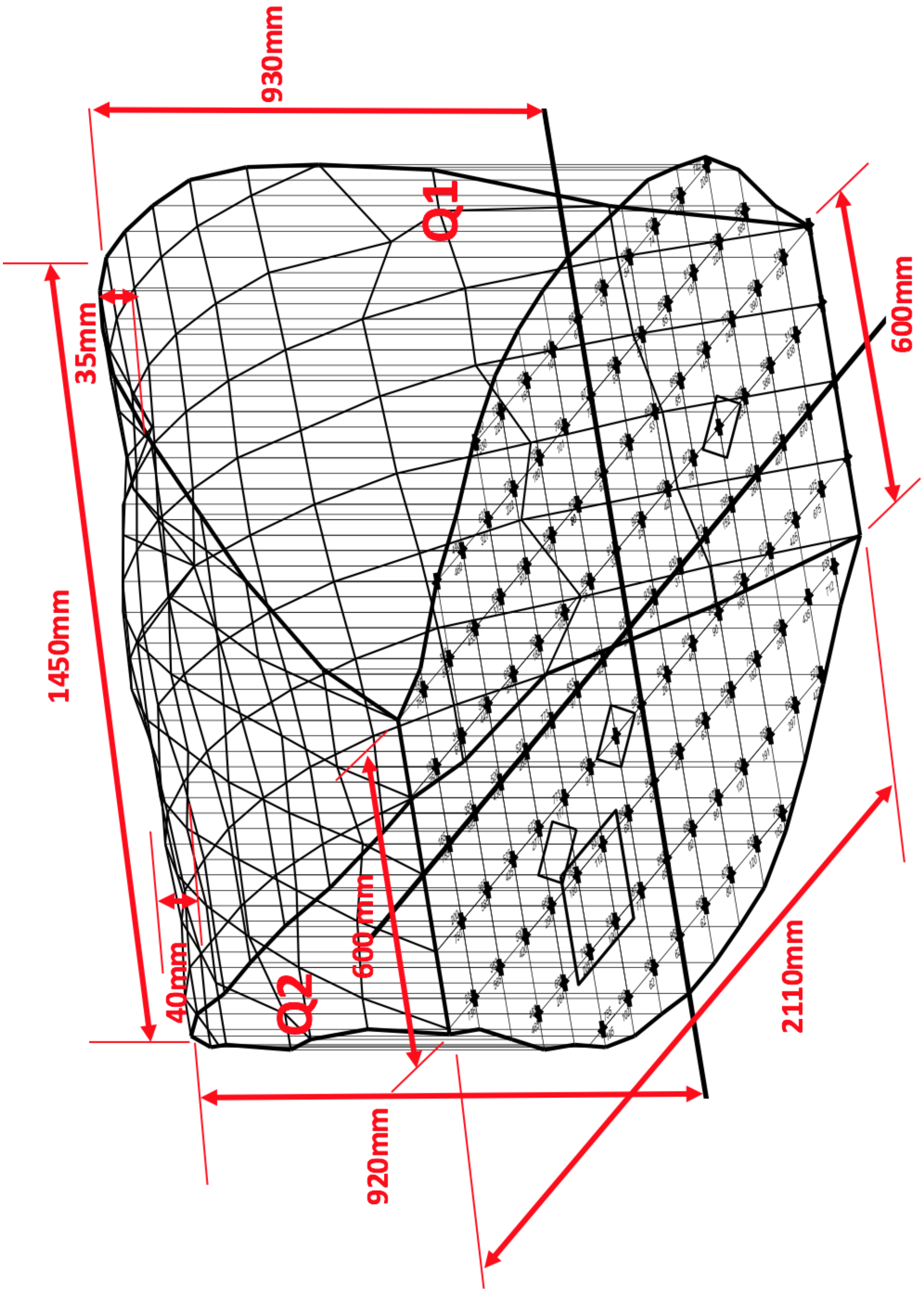


Fig. 9.41: Key Dimensions of Test Shell 4

9.4 Aesthetics Analysis

9.4.1 Geometry Analysis

Recording the surface geometry

A visual survey shows an asymmetry in the shell leaning towards Q2 described above matching movement measurements of the gridshell formwork (fig. 9.42)

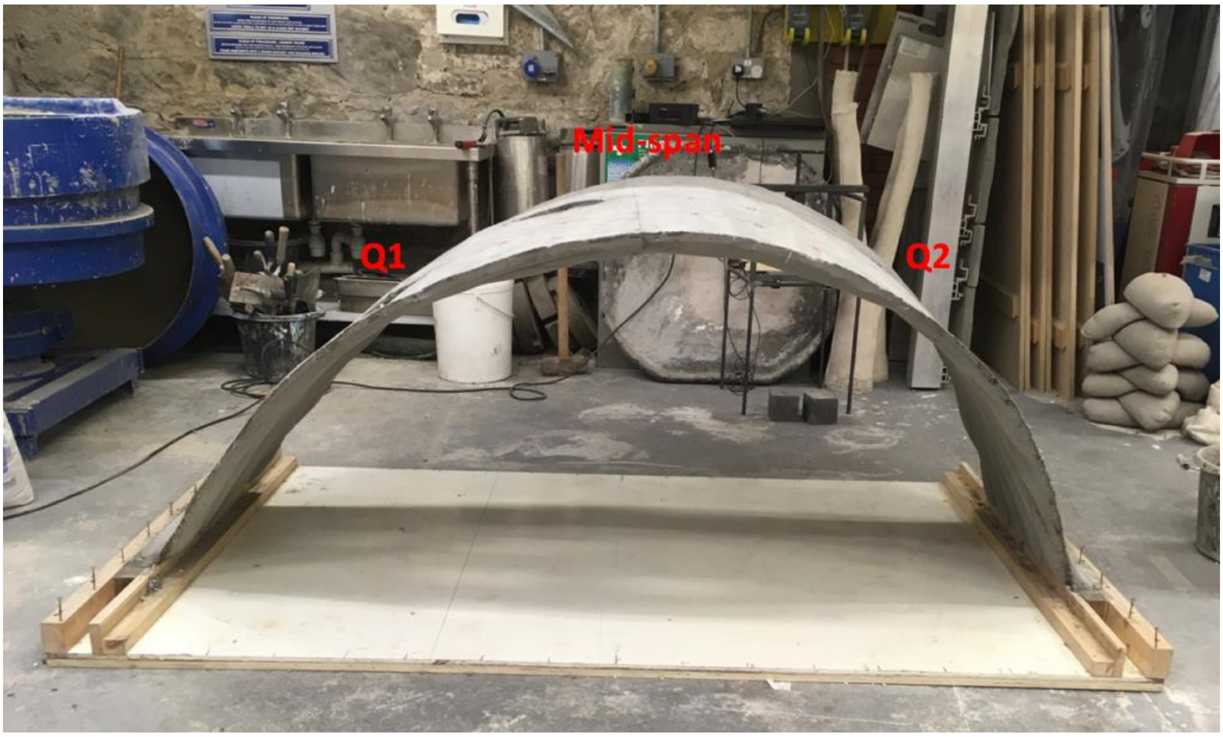


Fig. 9.42: Location of major points on Shell 4

As this asymmetry was imperative to understanding the geometry of the upper surface, a measured survey was conducted to understand the surface.

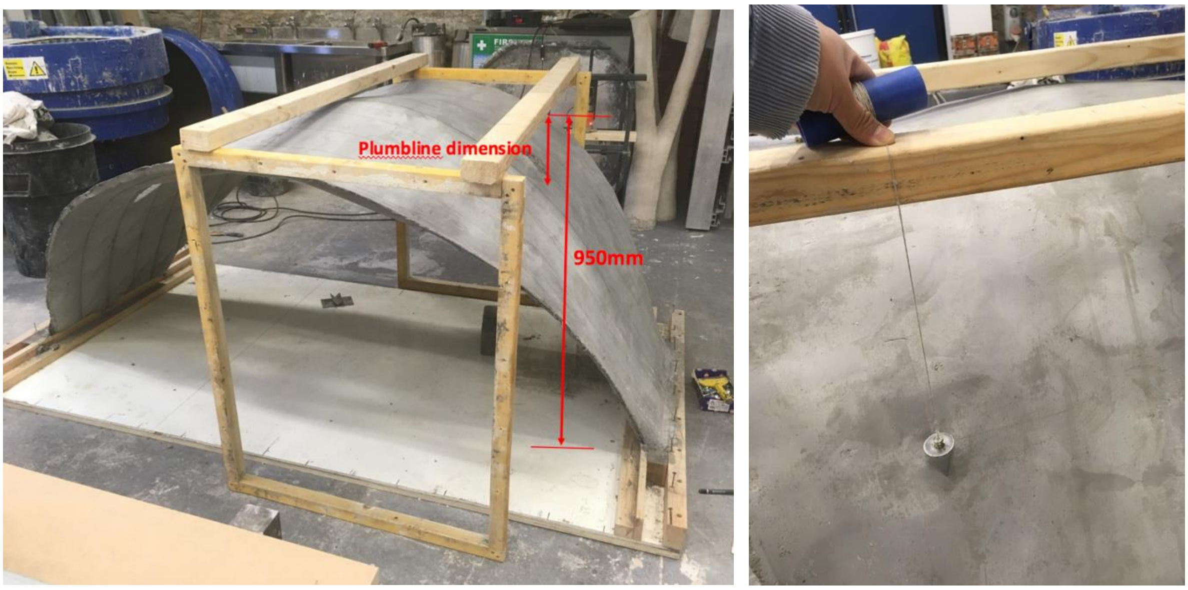


Fig. 9.43: Dimensional Measurement of Shell 4: system and sequence using plumb lines suspended from a timber frame

Fig. 9.44: Distances from the top datum are recorded on shell surface marked points at equal distances on plan. With these points marked, the distances of distance from frame and point is recorded directly on the upper concrete surface.

Methodology:

The shell was divided into 4 quarters on plan (see fig 9.45). The centrelines bisected the shell in x- and y- axes. A grid was marked out on the top surface, lines across 135 mm apart and lines along the shell 150 mm apart are marked. To record this point in space, a plumb line is dropped from a timber frame, moving along over the concrete shell measuring 950mm from the finished floor level of the shell. The shell height was found by simple subtraction.

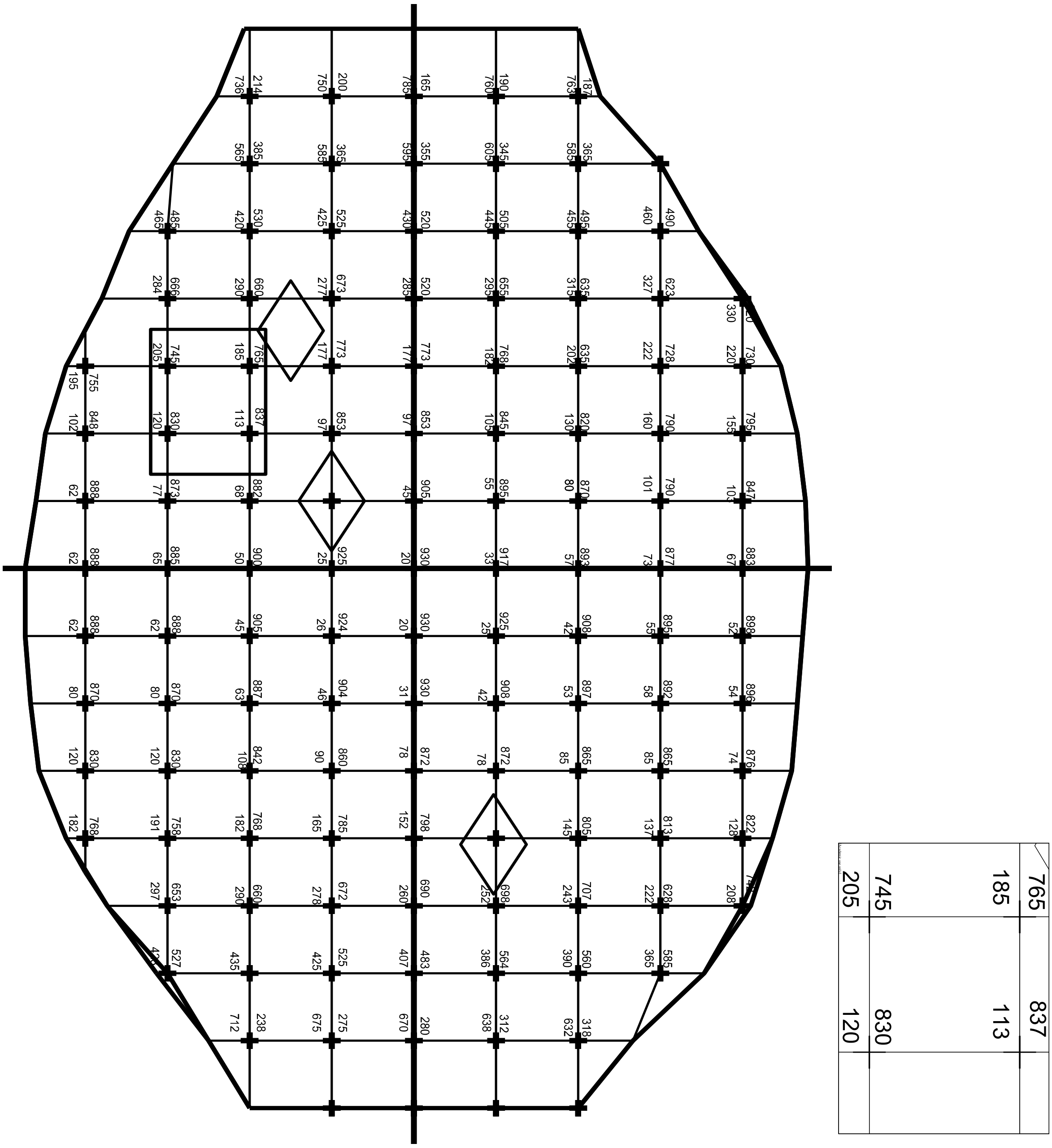


Fig. 9.45: The plan of the shell is divided into 4 sections. The distance from the 950mm high measuring frame was recorded. The height of this point from finished floor level was simply subtracted from 950mm. Excerpted from the larger plan diagram, the extract shows measured dimensions at the left of the intersection point. The worked out vertical distance from finished floor level is calculated by subtracting it from 950mm set as datum.

The method of measuring upper surfaces of the shells differed from the exercise carried out earlier on Shells 1 and 2. Whilst earlier exercises scanned the entire surface manually at 25mm grid to produce a detailed record of a predominantly singly-curved surface, this measurement exercise divided the shell into key sections to enable a digital model to be created with expedience deemed suitable for analysis by structural engineer.

9.4.2 Three dimensional study

Using these data, points are plotted into a three-dimensional digital model using CAD program (Bentley Microstation) to generate a 3d model. The digital model conformed to visual observation and displayed an asymmetrical geometry. It also described the geometrical variation at the apex of the shell and projecting edges. The results are displayed as follows.

Fig. 9.46 Side view comparison between digital and photograph of built model

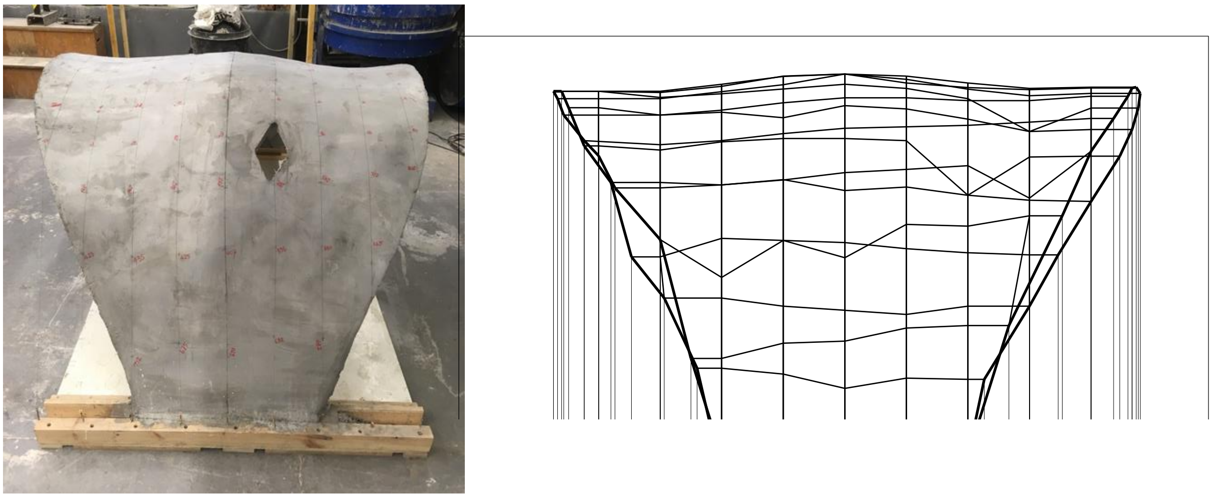


Fig. 9.47 Front view comparison between digital and photograph of built models

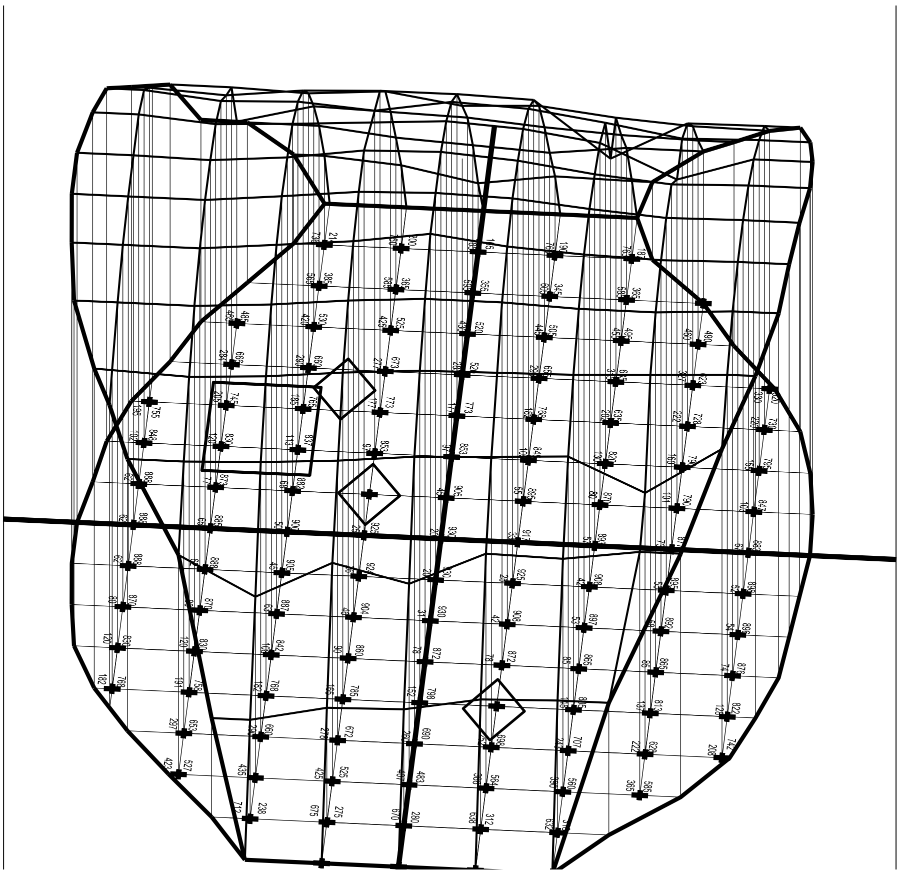


Fig. 9.48 Digital model of Test Shell 4

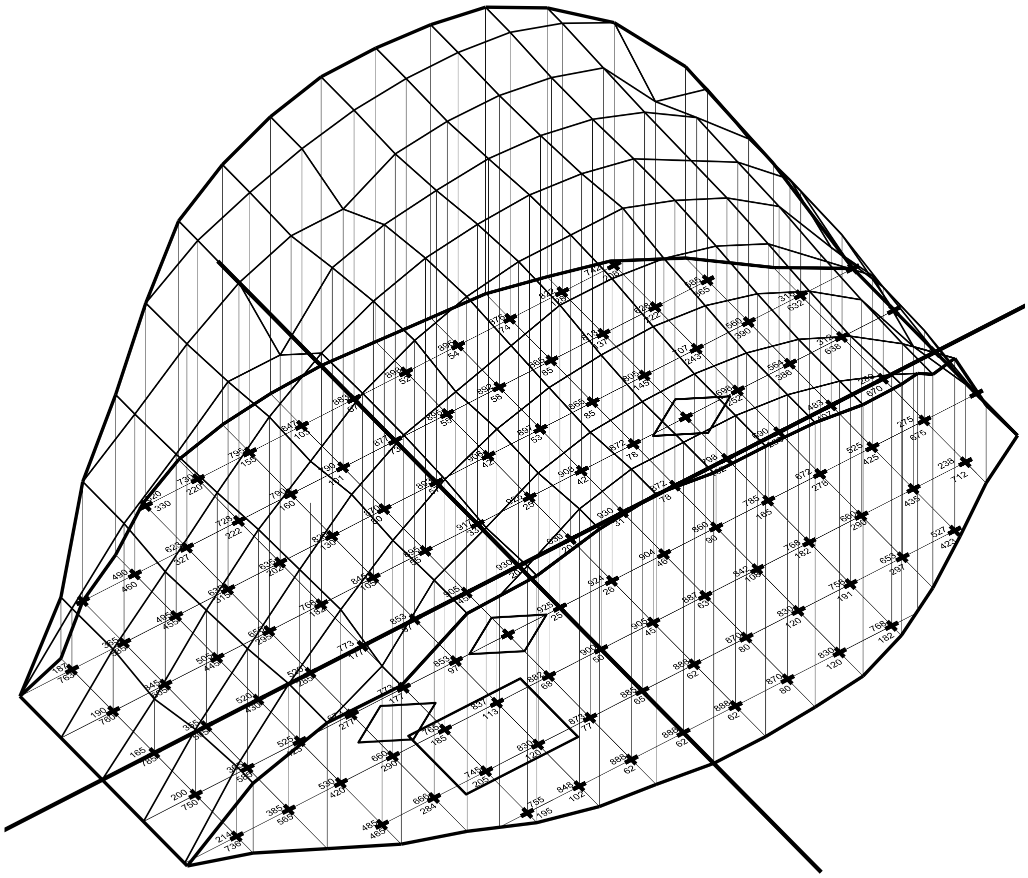


Fig. 9.49 Digital model of Test Shell 4

9.4.3 Shell thickness

The thickness was measured by using the same pair of callipers used earlier in test shells 1 and 2. It was observed there were cushions (thickest) and indentations (thinnest). To determine this range, the thickest part of the cushions and thinnest indentations were measured. The findings are represented in the reflected ceiling plan below.

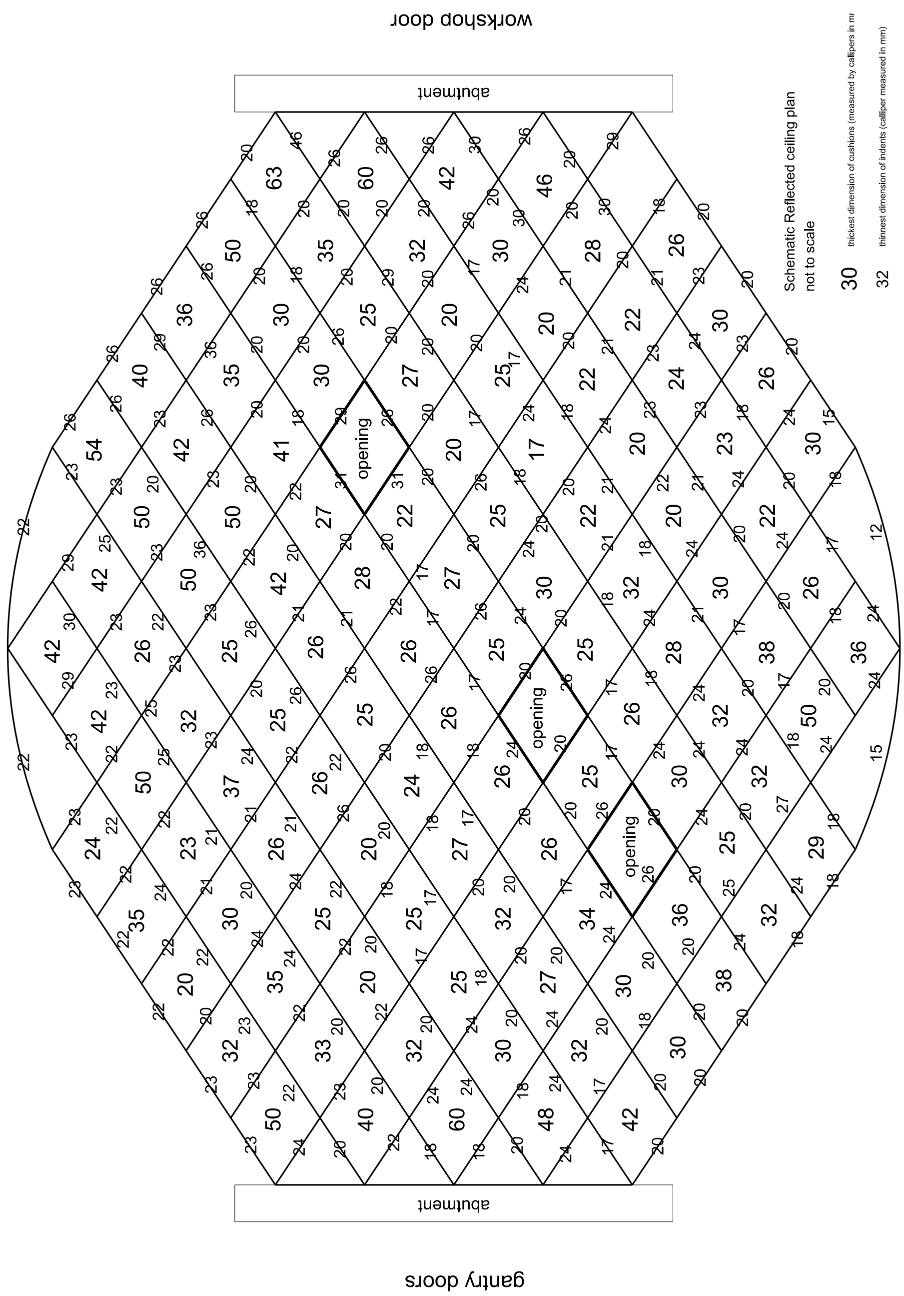


Fig. 9.50 Reflected ceiling plan of shell thickness.

These figures were input into an excel spreadsheet with geographical information for both cushions and indentation measurements. Arranged in this geographically accurate way in Excel, specific mean and average figures to the area of interest can be determined easily from the chart.

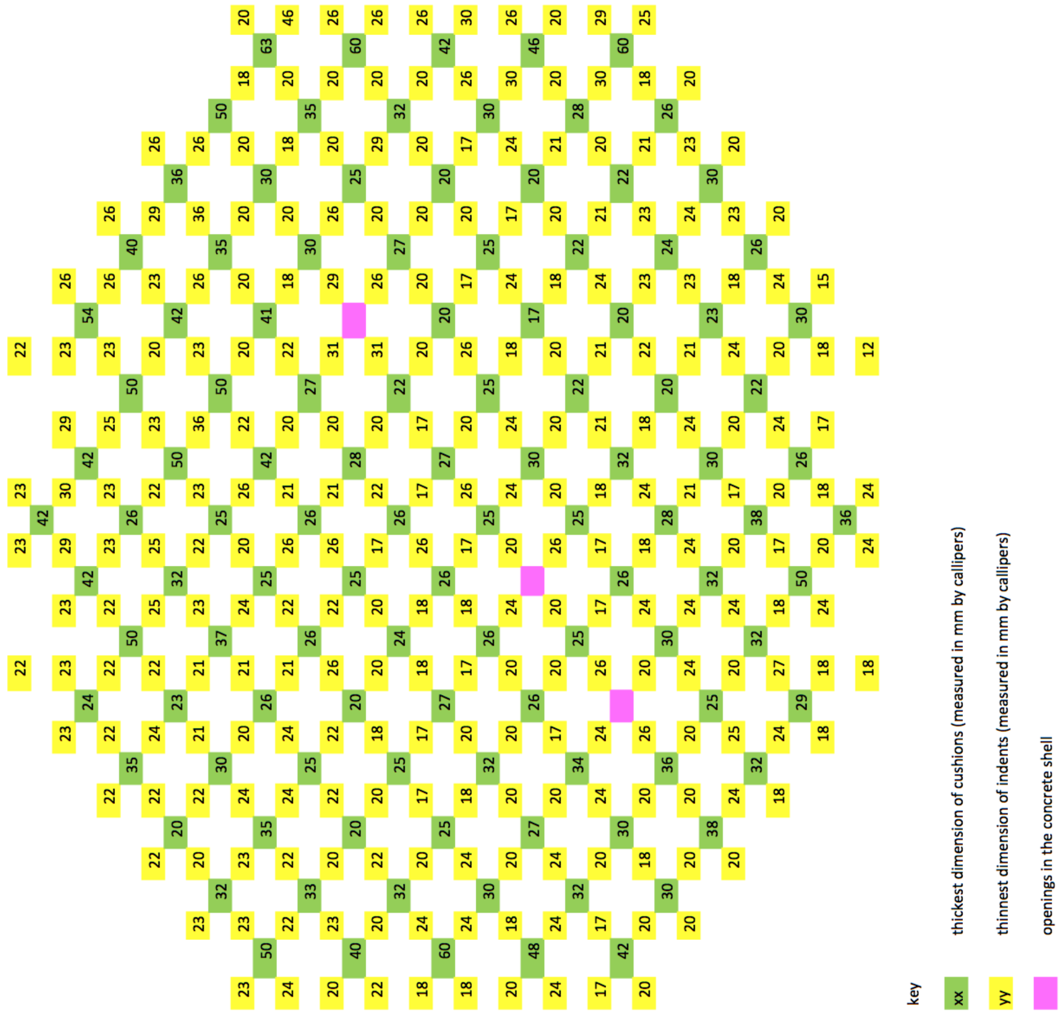


Fig. 9.51 Map of Thicknesses

9.4.3.1 Key results

The thinnest occurrence measured 17mm in the indentation line. The thickest occurrence measured 63mm in a cushion near the abutment.

The overall average (including both cushions and indentations) is 25.016mm.

The overall average cushions thickness is 32.01mm.
The overall average indentations is 21.968mm.

9.5 Structural Analysis

9.5.1 Failure testing

A pneumatic arm is set up directly above the shell to conduct a failure test. To induce an even loading, a steel spreader plate attached through plaster of Paris onto the concrete shell was set up.

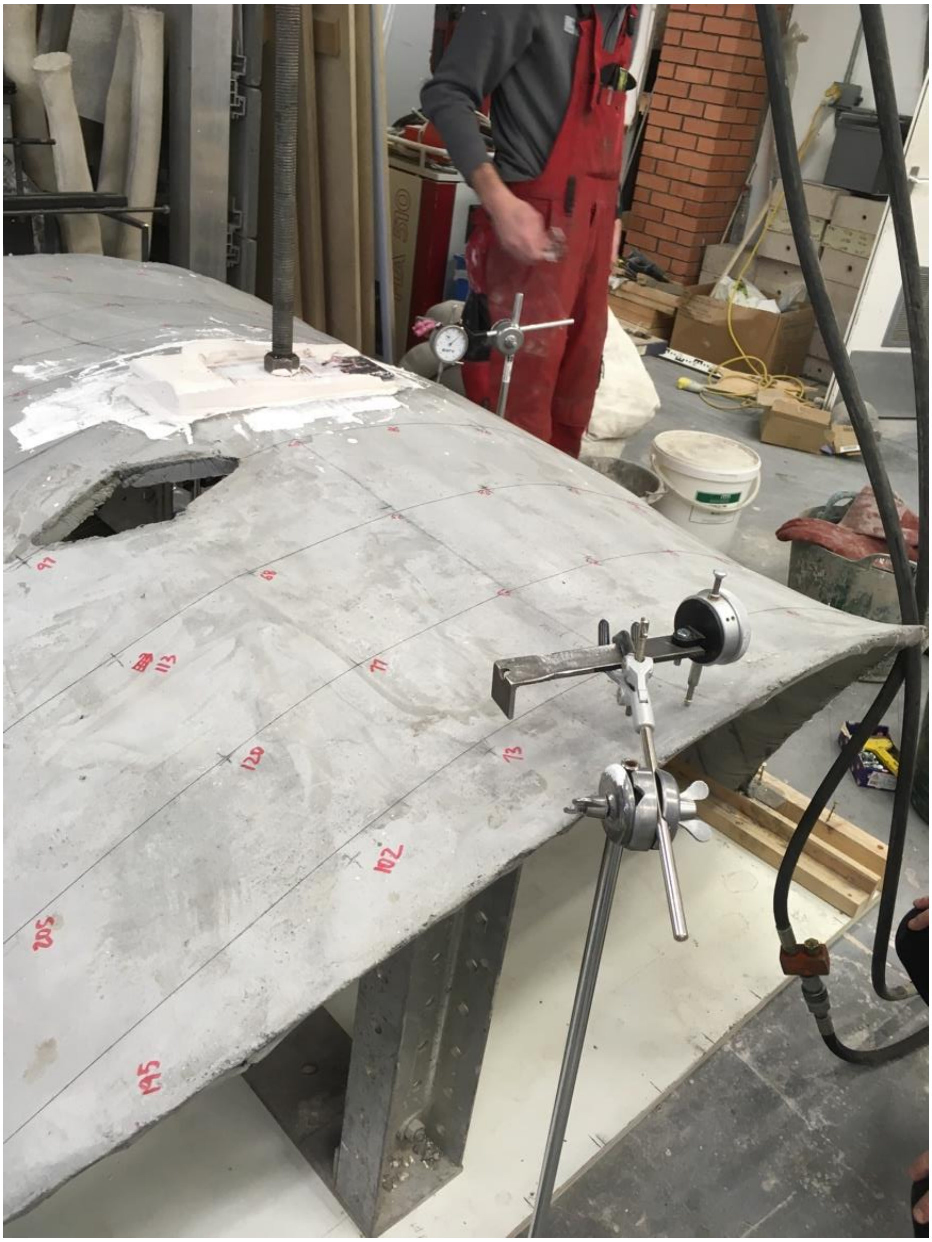
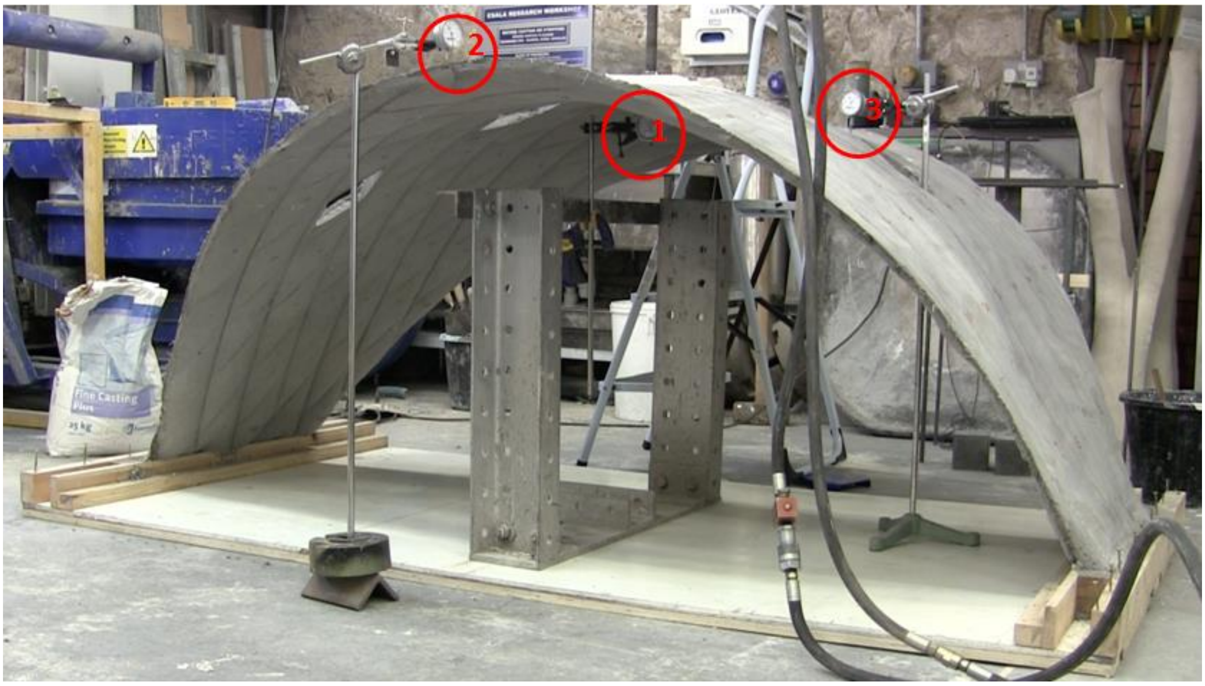


Fig 9.52: Plaster ensures forces are spread out evenly from hydraulic arm.

This load is introduced at the centre of the shell at the intersection between the two axes that bisect the shell on plan. To understand how the shell deflects to failure, three deflection gauges were installed - Gauges 2 and 3 were installed from the upper side and Gauge 1 from underneath to check for initial movements. The readings are presented as follows.



Load / kN	Dial 1 / mm (bottom –mounted)	Dial 2 / mm (top mounted nearside)	Dial 3 / mm (top mounted farside)
0	0.600	1.500	2.000
0.25	0.690	1.445	1.970
0	0.623	1.485	1.990
0.25	0.680	1.450	1.982
0.50	0.815	1.350	1.940

fig 9.53: a) top: dial locations
b) bottom: deflection readings

Structural Cracking appear with an imposed load of 0.70 kN

The experimental load-displacement curve obtained was shown in fig 9.54. From such a curve, it was possible to calibrate the value of the elastic modulus (E) to be considered in the finite element model, by matching the numerical output of vertical displacement, at 500 N vertical load, with the same value obtained from the test. The E-value of 16500 N/mm derived was within the range of values of elastic modulus for concrete found in literature. The numerical load-displacement curve is shown in fig 9.53 below.

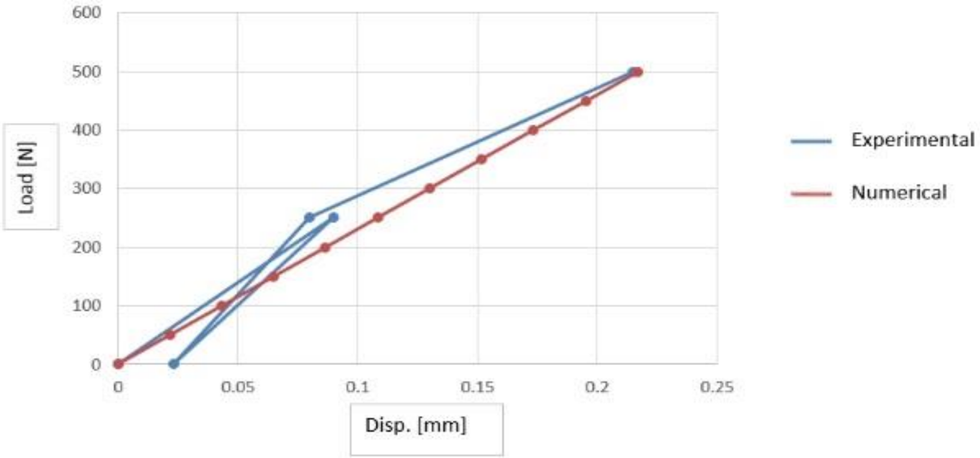


Fig 9.54: Load against displacement chart for Shell 4 failure testing (courtesy of B D'Amico of Edinburgh Napier University)

Fig 9.55: Failure under point load

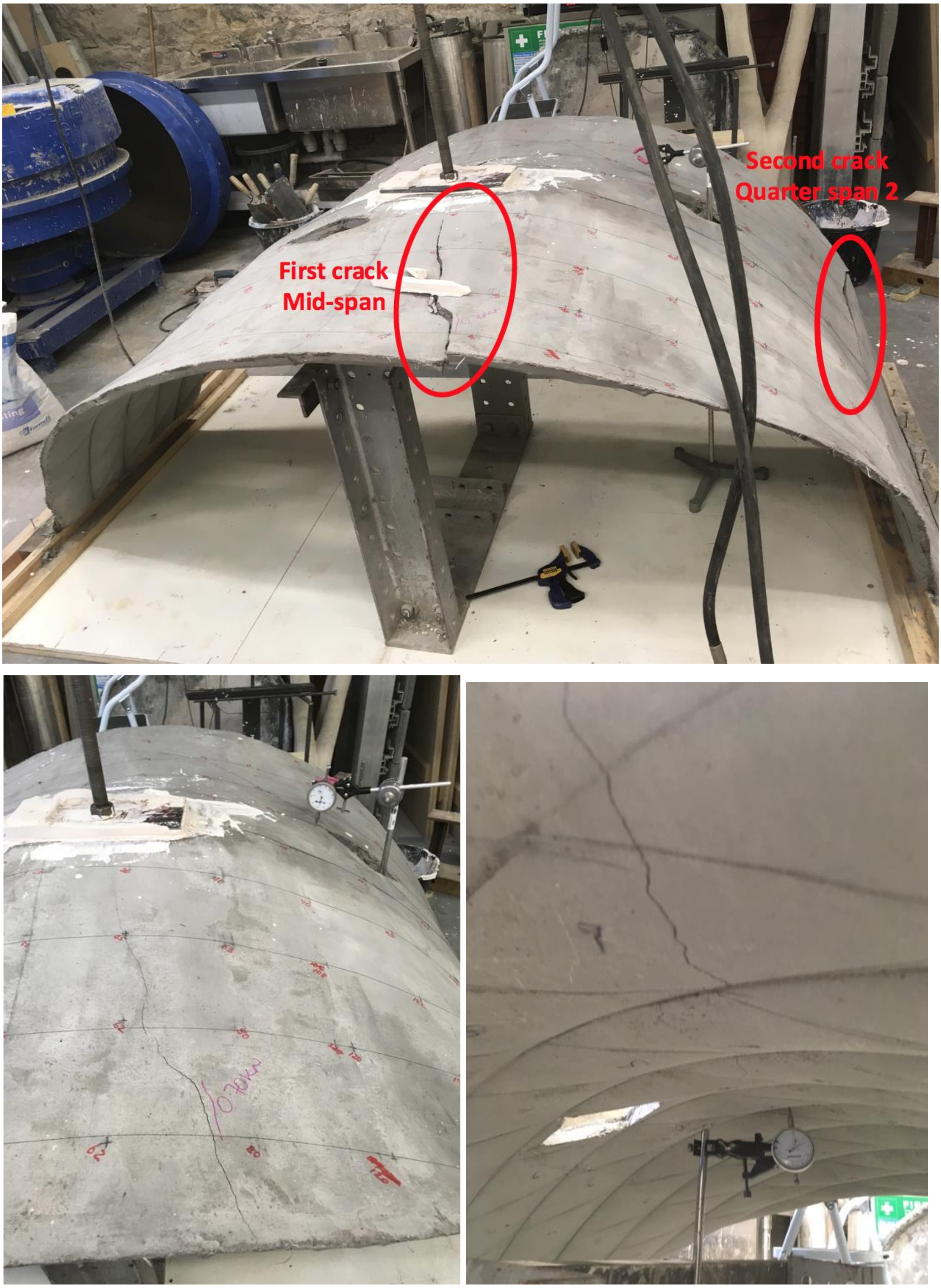


Fig 9.56: a) top: cracking patterns/ behaviour

b) first cracks appears from shell edges run through thickness

At 0.70 kN, the first structural cracking was noticed. The split can be seen on both top and bottom surfaces starting from the edge. Rather unexpectedly, the shell cracked at the apex of the shell and ran from one of the free-edge towards the centre of the shell.

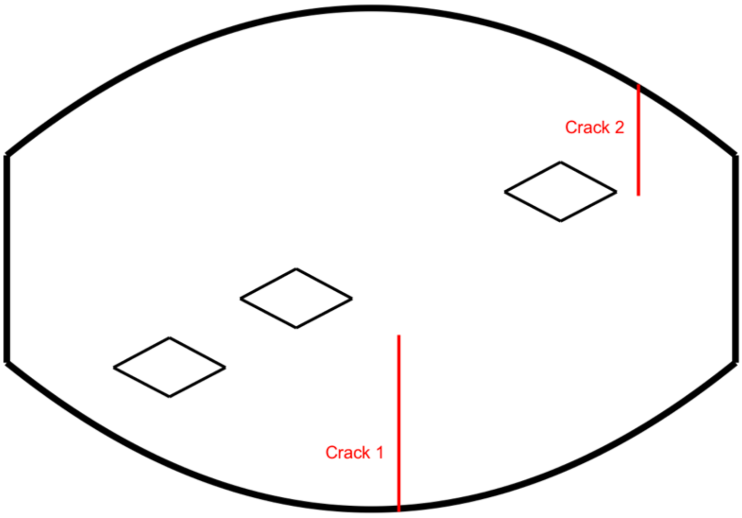


fig 9.57 Approximate location of cracks on concrete shell.

Through shell failure behaviour during failure testing for shells 1 and 2, one expects structural failure to occur at quarter span in shells. This crack runs through the thickness of the shell. The next section that cracked was at Q2 resulting (fig. 9.57) before the shell eventually collapsed completely.

fig 9.58: the shell completely breaks up

A few pieces of the shell remnants were checked for thickness and they measured in the range of between 20 mm and 35 mm.

fig 9.59: thickness measurements of broken sections between 20mm and 25mm.

The test is summarised dimensionally and graphically:

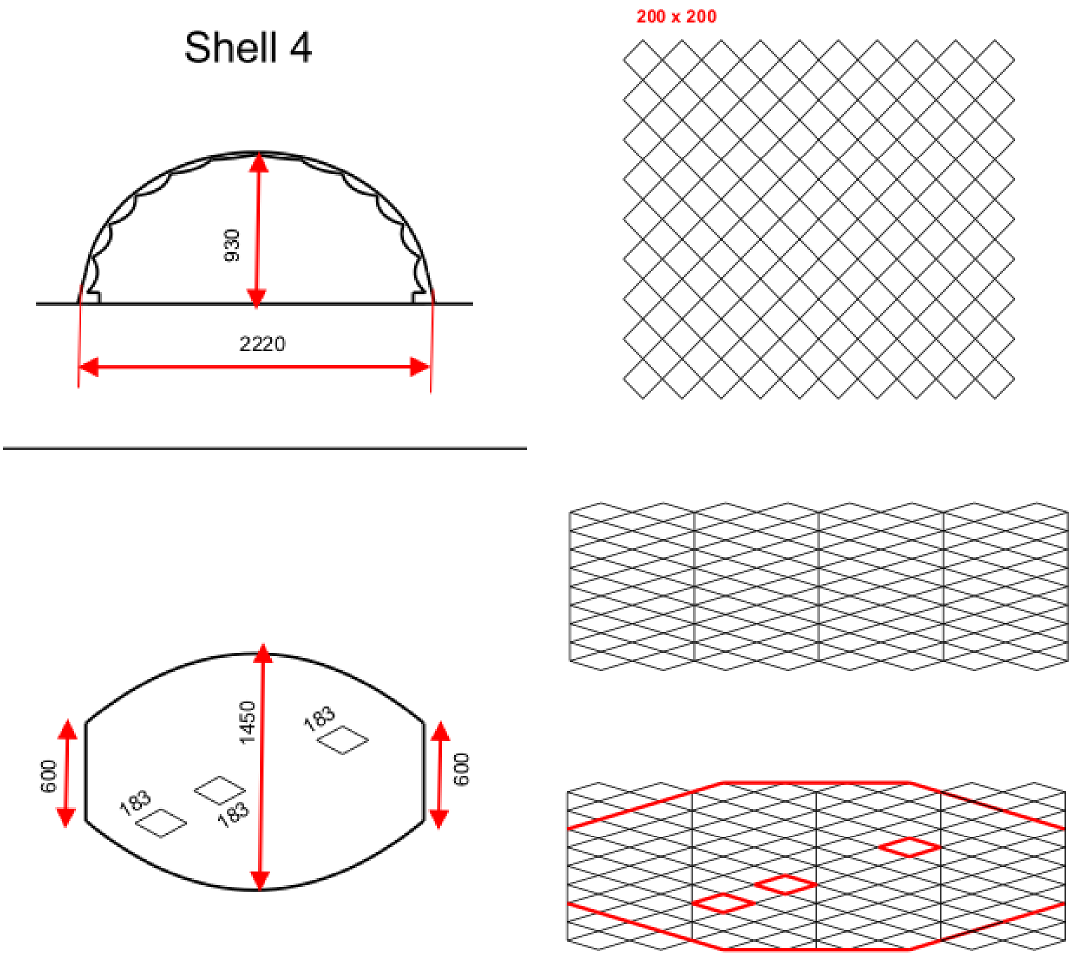


fig.9.60 The gridshell could be trimmed differently at the edges before concrete is cast. The minimum width dimension of 600mm was recorded at the abutment channels while the mid-span width measured 1480mm.

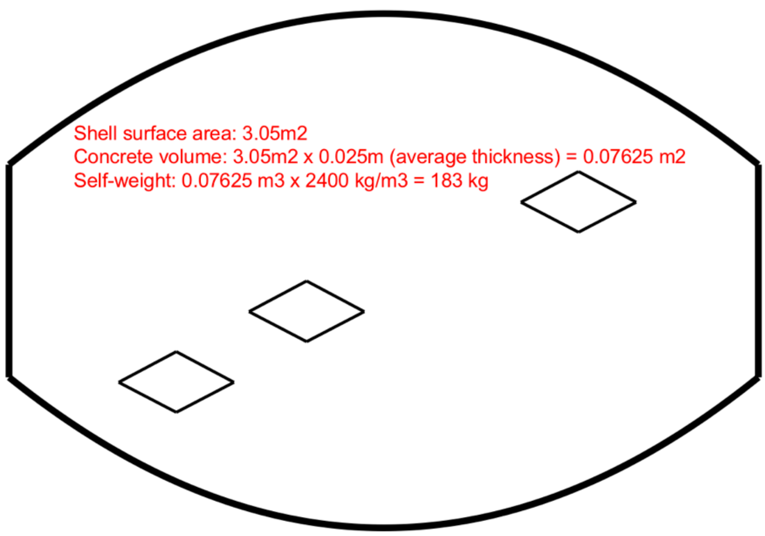


fig. 9.61 The gridshell could be trimmed differently at the edges before concrete is cast. The minimum width dimension of 600mm was recorded at the abutment channels while the mid-span width measured 1480mm.

9.5.2 Self-weight of test shell 4:

Area of Shell according to digital model : 3.05 m2

Assuming average thickness of concrete as 25mm ie 0.025m

Volume of shell = 3.05 x 0.025m = 0.07625 m3

Self-weight of shell = 0.07625 x 2400kg/ m3 = 183 kg

9.5.3 Mathematical and structural analysis (with the support of engineer Dr Bernardino D'Amico of Edinburgh Napier University.)

A FE model of the concrete shell was created by Dr Bernardino D'Amico and calibrated to understand the load-carrying capacity of the shell. The geometric survey and corresponding FE model are shown in fig. 9.62 below. The variable thickness of the shell was modelled by assuming the constant average value of 22 mm. In the FE model, the supports are modelled as pinned.

Fig 9.62 Digital model of shell. (courtesy of B D'Amico of Edinburgh Napier University)

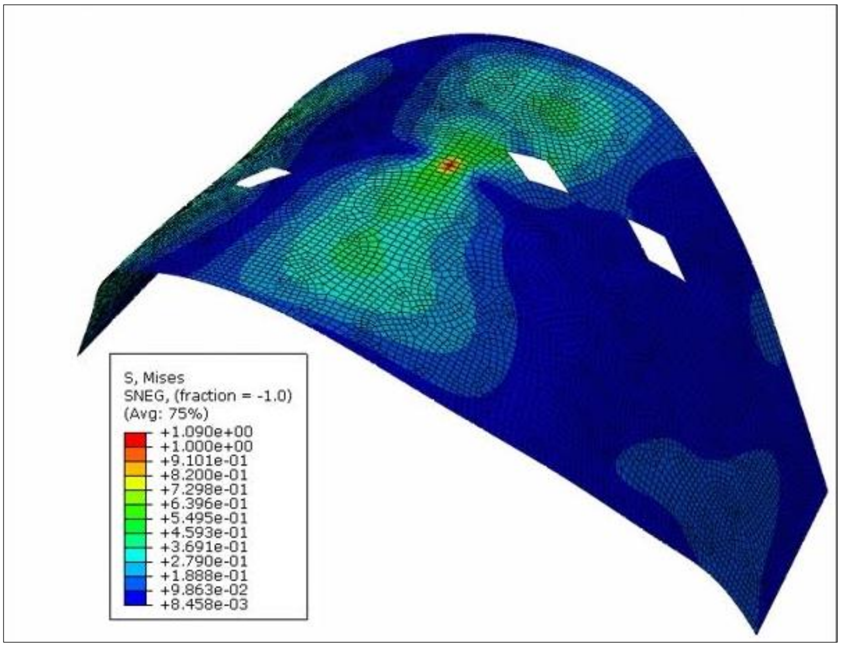


Fig 9.63: Stress distribution under the effect of a concentrated load. Areas of major stress are found at the external sides of the shell mid-span. (courtesy of B D'Amico of Edinburgh Napier University)

For the FE analysis, a point load of 500 N i.e. 0.5kN was applied at the centre of the concrete shell, and the corresponding vertical displacement (at the point of applied load) was recorded. According to the FE analysis model, high stresses are found at the areas near the abutments. This confirms the forces concentrating towards the abutments giving rise to increased stresses. This can be represented in the figure below fig. 9.64.

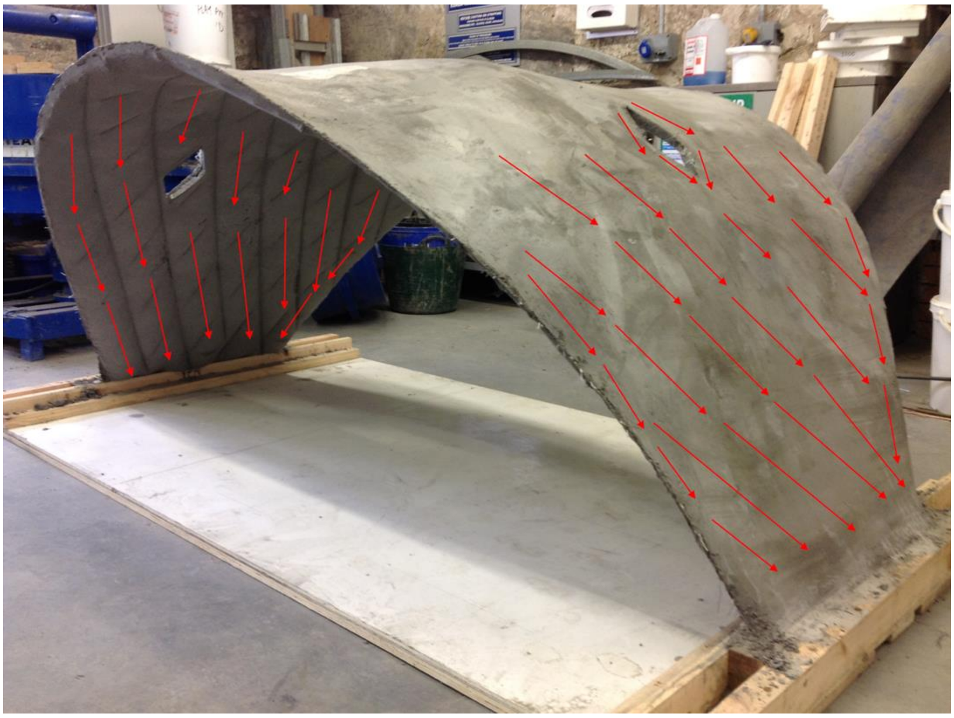


Fig 9.64: Stress distribution of the concrete shell sees concentration of forces along the corrugations transmitting to the abutment points.

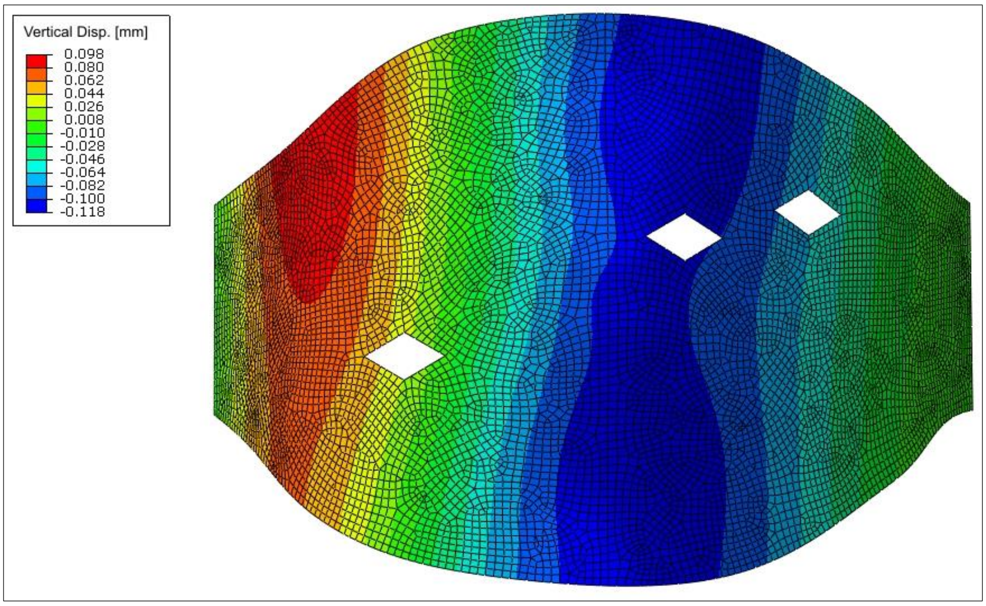


Fig 9.65: Gradient of vertical displacements under the effect of a concentrated (500 N) load. Negative values indicate downward displacements. The asymmetrical stress distribution results in an asymmetrical stress pattern. The asymmetrical stress pattern is attributed to the asymmetrical nature of the shell. (courtesy of B D'Amico of Edinburgh Napier University)

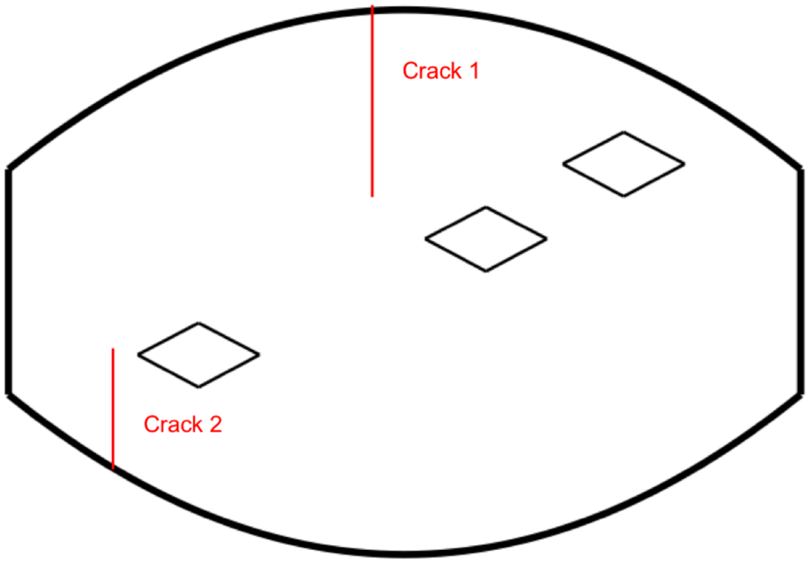


Fig 9.66 Approximate location of cracks on concrete shell.

During the test under point load, first cracks (tears) started to appear at the external sides of the shell mid-span (see Fig. 9.66), rather than on one quarter of the span (expected for a barrel-like shaped vault). An explanation for this can be found by considering the shell has a slight curvature in the transverse direction as well, which induced in-extentional (tensile) deformations at the edges. Interestingly, the FE gives confirmation of this, by showing high concentration of stress.

9.6 Further questions/ research

Although this novel method of concrete shell construction was developed to produce a shell with complex curvatures, how this method can be applied at a larger scale has to be explored further, opening further questions.

9.6.1 Gridshell Formwork:

Scale and extent is crucial. Test shell 4 shows a system constructed from 3m laths at the maximum and without jointing. Theoretically, these laths could be joined together in sections reminiscent of the way sections joined together at NARA Silk Road exhibition (Chilton and Tang, 2017 p100). This possibility was useful for transportability as they can be pre-assembled off-site and joined together when on site. Concrete can be applied after the fabric is draped over the gridshell section.

9.6.2 Fabric size

When the concrete structure size is increased, the fabric upon which concrete is applied needs to be increased to cover over the gridshell. The fabric need to be stitched together first and then stretched into shape. This may require the expertise or involvement of installers of tensile membranes structures to ensure the fabric is cut and designed to allow sufficient draping for cushions to form during concrete casting.

9.6.3 Re-configurability

The re-configurability of the system depends on how these tubes could be connected and joined together. Having to ensure they could be joined together, these may become difficult to handle if they are excessively long. However, these are much stiffer than timber and are less susceptible to fracture and damage. However, should they fracture, due to their fibrous nature, these areas possibly be bound and taped together and repaired.

9.6.4 Concrete application: Shotcreting

Mechanization may replace time-consuming hand trowelling to increase speed and evenness of application on concrete. During a recorded interview with Bill Jones, president of the sprayed concrete association of Great Britain with more than 40 years' experience of working with sprayed concrete, the material can be sprayed easily and evenly onto fabric formwork. Sprayed concrete is suitable even for application on the underside with sufficient adherence. Applied at a distance of one metre away from the surface and in numerous concrete coats, sprayed concrete should be applied from the top moving down the sides. The first flash coat (10-12mm thickness) will become the base coat on which subsequent layers of concrete may be sprayed in order to build up shell thickness. Jones expressed excitement and strong confidence that sprayed concrete will be suitable for creating concrete shells on a GFRP gridshell formwork even at height as in the previous use of sprayed concrete of The Cacoon at The Darwin Centre by CF Moeller completed in 2010 (Jones, 2016). This may form the basis of further study and research.

With this small scale prototyping, it was possible to apply the concrete onto a shell about 900mm from the ground without any support. At a bigger scale, the gridshell may need temporary scaffolding towers for support to minimize deformation. These scaffolding towers may form the support for the sprayed concrete machines to stand on or be attached to. If scaffolding technologies are used, this solve the issues of height. If scaffolding is located from below, the interior of the surfaces may be sprayed using a dry mix. This is likened to spraying the tunnel for reinforcement. Unfortunately, the gridshell will be above the concrete shell and will be needed to dis-assemble and be removed from the upperside.

Another method of using spray concrete is to use cranes and cherry pickers for robotic arms to spray the concrete onto the fabric from the top. In this way, the gridshell formwork will be on the inside of the finished surface and can be taken apart in sections before being moved away and reused.

9.6.5 Foundations and Abutments

The abutments for test shell 4 were integrated into concrete shell. At life scale, excavated into the ground, with groundwork design by an appropriate engineer, the shell may be complete at one single casting. Foundations that are integrated as substructure are important elements of shell designs. This improves the initial pre-cast concrete abutments and contains an actively-bent gridshell formwork. However, these suggestions are not generic and abutment design needs to be integrated in the design process.

9.6.6 De-centring Process

The method by which the gridshell is removed after the casting is an important point of consideration. Issues such as safety and accessibility, and in what forms (whether in sections or collapsed) the gridshell will be removed safely from underneath the shells. Whether they are removed as one single piece or in a number of separate sections are important factors that need to be considered carefully.

If there was a space under the shell, the gridshell could be removed from under the new concrete shell similar to the removal of an arch centring once arch construction is complete. On an industrial scale, to increase accuracy, temporary scaffolding/ supports would be needed and should be devised with structural engineers. The shell could also be designed as structures "lifted up" from the ground like the Orvieto aircraft hangers by Luigi Nervi built during the 1930s. This effectively leaves a space below for the formwork to be removed, collapsed and removed off-site.

9.6.7 Openings

Rather excitingly, this gridshell formwork also demonstrated the possibilities of creating openings within the concrete shell. Window sections could be inserted/set into the concrete first. The experimental build also proved that openings can be prepared individually and this can affect internal atmospheres.

9.7 Discussion

The test results are discussed under three headings:

- Construction (behaviour of gridshell formwork during casting)
- Aesthetics (of concrete shell)
- Structure (structural strength of resulting concrete shell.)

9.7.1 Construction

The construction discussion will be divided into the following sections:

- Gridshell formwork construction (including fabric formwork)
- Concrete shell construction (casting)
- Gridshell formwork removal (decentring)

Gridshell formwork construction (including fabric formwork)

As a gridshell formwork material, GFRP was flexible and stable compared with gridshells made from previous materials (PVC, metal and timber).

The decision to drill small holes through the glass fibre tube gridshell tubes avoided removing excessive material from the tubes which weakened the material. The use of steel wires allows the gridmat to move and slide, yet remaining intact. It could bend easily but strong enough to revert to its original shape without snapping. As this may not be viable at a larger scale and may impact on lightness and accuracy, alternative systems of connecting grid laths to form the gridmat will need to be developed.

With GFRP tubes removed, the resultant gridmat returned to its original position easily. When it was preliminarily restrained by adding pvc tubes, the fixed gridmat could be further manipulated by pulling them together or pushing them apart to accentuate double curvatures. This was a way by which complex curvatures may be created. Additionally, the formwork was also responsive to imposed forces to create pronounced curvatures. The double curvatures also helped the gridshell (and eventually, the concrete shell) to develop stiffness. The use of a cheap material like pvc conduit tubes as bracing implied a minimization of cost and maximization of workability.

The gridshell could be trimmed differently at the edges before concrete is cast. The minimum width dimension of 600mm was recorded at the abutment channels while the mid-span width measured 1480mm.

The fabric used was finer gauge cotton than the rough geotextile used earlier. Contrary to expectation, the concrete keyed well onto the fabric to produce a fine finish.

The fabric stitched onto the gridshell pulled it as tight as possible to prevent any creases or wrinkles. Stitching the fabric formwork was a better way of controlling the tightness of the formwork compared to test shells 1 and 2 which used a hemmed detail. Stitching ensured no wrinkles were visible in the formwork. With a tightly stretched fabric on the free edges of the gridshell, a thin shell with shallow cushions was achieved. The simplification of abutment design also meant that anchoring and shells of this size could be completed in a single casting although metal re-bars may need to be used to connect the shell structurally to the abutment restraints and foundations.

Formwork was decentred easily, especially when compared to the metal gridshell. The concrete shell was stable and monolithic as the shell was joined onto the abutments as one single entity. This connection may be reinforced and made stronger by steel re-bars.

Fig. 9.67: The patterns of GFRP gridshell were lightly imprinted on the under-surface of the concrete shell.

At first look, Test 4 followed the doubly-curved gridshell formwork. However, upon measurements, an asymmetry was present. This was largely due to the construction process, suggesting that to increase geometrical accuracy, the formwork will need to be more rigid. This can be achieved by increasing bracing to triangulate. The other way is to pre-stress the shell by increasing curvatures, and/or the introduction of vertical props can also help to stabilize the formwork whilst concrete is applied. Another suggestion is to tie the shell at abutment locations. By attaching gridshell ropes as described by fig. 9.68, without the shell becoming slack, the desired curvature can be maintained. This was also employed by Waller to maintain funicular geometry of the arch beams in his Ctesiphon vaults construction as shown in fig. 9.69.

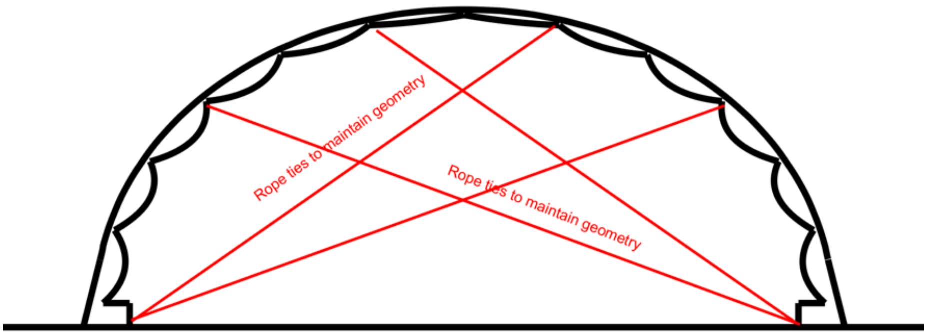


Fig. 9.68: The patterns of GFRP gridshell were lightly imprinted on the under surface of the concrete shell. The concrete cushioning produced is also much more controlled in terms of thickness.

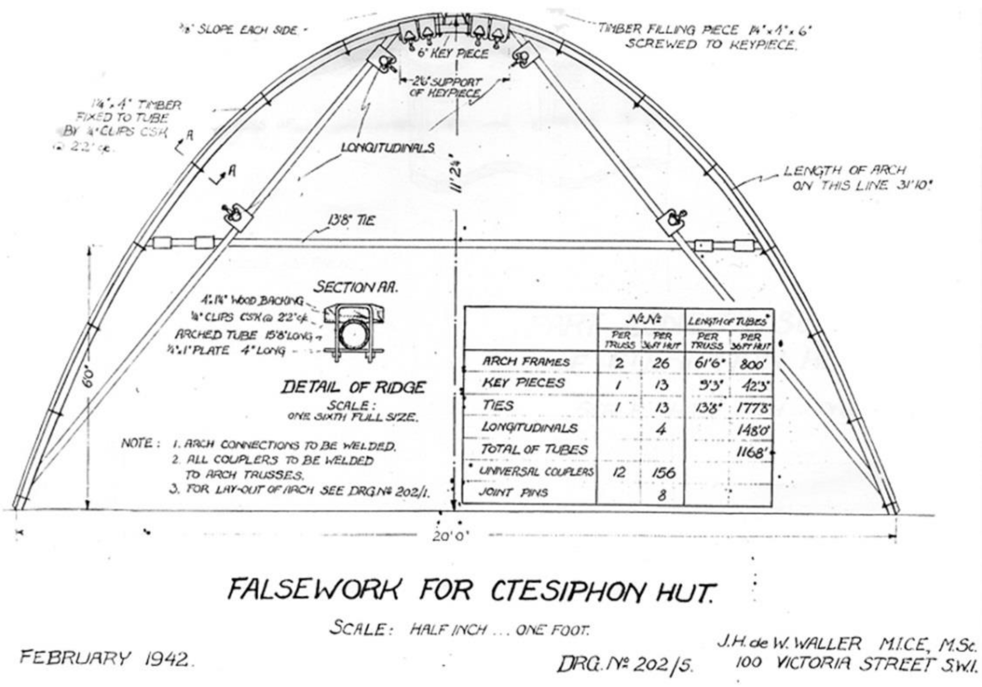


Fig. 9.69: James Waller made use of scaffolding poles to maintain the funicular curves of the shells.

9.7.2 Aesthetic

Compared to previous tests, Test Shell 4 was most complex in shape terms as it incorporated double curvatures and flared edges with openings. The shape of this shell was intimately related to the method by which formwork was manipulated: the double curvatures were a result of pulling and pushing the grids of a deployable gridshell restrained at particular lines i.e. at the areas near the abutments. A shell of this shape and geometry can be achieved by digital form finding, this process allowed the designer the freedom to adjust and design geometries to tailor shapes to formal requirements.

With the openings, light penetrated into the spaces below. Apart from the interior spaces, light also illuminated the cushions to express them differently from Test Shells 1, 2 and 3 where we saw light entering from the sides, rather than from the top. This possibility meant that the spaces defined by the shell can be lit and ventilated especially useful if it was a deep planned shell.

Using GFRP as gridshell formwork transformed the resultant shell in shape, but also become much stiffer as a result. This testifies to the GFRP gridshell being intuitive and responsive to help develop a usefully non-mathematical understanding of a gridshell behaviour helping the designer/ architect/ engineer understand such materials.

The leaning outwards or cantilevering of the shell is another demonstration of what this system could do. Deemed more interesting than straight edges, the lines provided by the gridshell could form guidelines to where gridshell edges can be situated..

Here, gridlines of the gridshell resulted in the patterning on the under surface of concrete shells. This prototype demonstrated how the positioning of resist impactos to form openings can be guided by the grid patterns to form a cohesive architectural language.

The resulting pattern was reminiscent of Nervi's diagrid pantograph patterns in the underside concrete roofs of the 1960 Palazetto dello Sporto, Rome and the semi-circular dome of the Salone B exposition roof in Turin, Italy. These shells conceived in the late 1940's were built quickly and cheaply.

The immediate difference between Nervi's shells is visual and seen from the interior. Firstly, Nervi's shells are deeply set, brought about by pre-cast travelloni employed (see Chapter 3.6.2.1).

Fig. 9.70: The patterns of the Palazetto dello Sporto by Luigi Nervi 1960 in Rome.

In Nervi's shells, concrete travellonni were pre-fabricated on the ground in diagrids of pre-calculated dimensions. These travelloni have raised edges which when inverted become the ribs visible from the underside. Once placed in position, concrete was poured in channels which allowed these travelloni to be stitched together first by steel wires, then by concrete poured into the channels (fig 9.71). These processes take place at height, positioned on temporary falsework. Secondly, unlike this research hypothesis, in Nervi's method, the scaffolding or falsework does not have a shaping influence on the completed concrete structure as shell forms are conceived and pre-determined. In other words, scaffolding was merely functioning as support which is unlike the gridshell that is adjustable and determined the shapes of the final shell. Thirdly, the difference between ribbing and skin appear distinctly separate although they are integral. Fourthly, to the layperson, an appreciation of the construction process may not be most straightforward. Lastly, although cheap and quick to construct, this method of construction resulted in forms which are generated from revolutions of lines or curves resulting in platonic synclastic and monoclastic forms.

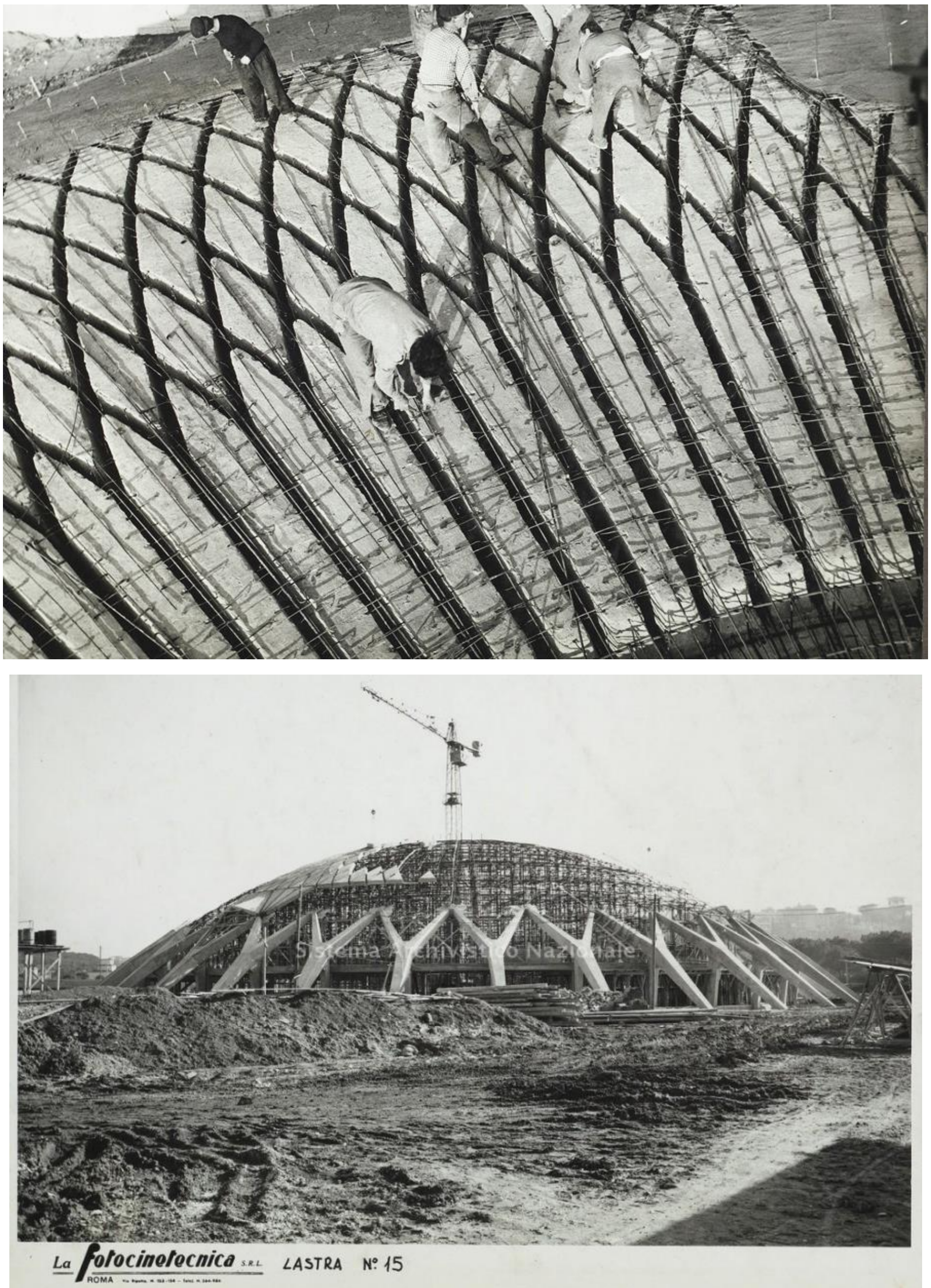


Fig. 9.71: Travellonni connected together above an intense forest of scaffolding (photo from (Fondazione MAXXI Centro Archivi Architettura, fondo P.L. Nervi)

Fig. 9.72: The patterns of the test 4 clearly suggest the method by which the shell was constructed with gridlaths clearly imprinted on the under-surface of the resultant concrete shell.

The expression of the pronounced and complex double curvatures was made possible by the use of GFRP tubes which possessed desirable elastic and stiffness. This quality has been used in larger scale projects by Bavarel and Genangal (2011 and 2012) both of whom worked extensively with these materials to create lightweight structures gridshells. GFRP has enabled the shells to develop and readjust their morphology to achieve additional stiffness. The attractive stiffness is largely attributed to material, supporting the suitability of GFRP tubes as material for use as gridshell formwork. With both geometrical accuracy and controllability, the resistance and strength direct them as gridshell material for formwork making.

The new shell also demonstrated the effects of openings for light to enter the space to illuminate interior spaces. This light allowed the undulating surface cushions to be viewed, enjoyed to create a comfortable environment.

Abutments have evolved to a very simple form. In a building project, it may be necessary to install specialist foundations designed with properly reinforced by re-bars with a structural engineer.
The instant reversion of gridshell into the original flat position makes it reusable. The configurability is also very clearly seen in the numerous forms that have become possible by manipulating the gridmat in different ways.

9.7.3 Structure

The underside of the shell displayed the finest concrete finish in all test shells concrete finishes. From calliper measurements, and like all other tests the shell developed shallower cushions at the mid-span apex and thickest cushions at abutments. However, the shell failed at a lower loading, recording first cracks when forces were applied at 0.7kN (70kg/ 183kg) i.e. 38.25% of deadweight. This ratio is remarkably lower than that for Test 1 and 2 and was due to the shape and flared edges of the shell.

Test 1	393%
Test 2	432%
Test 3	4.9% to 9.8%
Test 4	38.25%

Fig 9.73 : failure load to self-weight ratio

This low failure load suggests attribution to two reasons:

Firstly, the tapering contacts at the abutments resulting in the concentration of forces focussed at the two abutments. Tests 1, 2 and 3 had straight abutments which load is transferred onto the ground. In test 4, the abutments are tapered, meaning that loads are concentrating at these points to transfer loads onto the ground. One possible way to improve this is to increase the abutments and taper the shells towards the middle such that it resembles a bow-tie on plan.

Secondly, the asymmetrical nature of the shell and the unbalanced shape of the shell may also have caused the shell to fail at this low loading.

The first cracking location was surprising as the expectation was for the shell to develop cracks at quarter spans areas, not the edges. This unusual occurrence may have been due to:

- the splaying out/ cantilevering form of the new concrete shell, as presented on the finite element model and
- asymmetrical nature of the concrete shell

The failure behaviour also showed fissure tears occurring at the apex at mid-span. Confirmed by finite element analysis carried out, steel bars/ reinforcements need to be embedded within concrete along the flared edges to counteract fissures/ tears. This can also be corrected by thickening the edges at free edges to strengthen the shell. Alternatively, to express shell thinness, this reinforcement may also be pulled back similar to the 1960 Barcardi factory (fig. 9.1)

Fig. 9.74: The patterns of the test 4 clearly suggests the method by which the shell was constructed with gridlaths clearly imprinted on the under-surface of the resultant concrete shell.

9.8 Conclusion

The chapter has set out to explore the three main aims:

1. Firstly, complex curvature through use of glass fibre reinforced polymer gridshell.
2. Secondly, the creation of free edges that did not extend to the edges of the gridshell formwork
3. Thirdly the casting of openings in concrete shells.

The test shows results to prove the feasibility of using this method.

The use of glass fibre reinforced plastic rods was effective in creating double curvatures. By pushing and/ or pulling the gridshell, the shell developed better curvature definition. This ease resulted in a shell that replicated this geometry.

Although the construction proved the free edge possible, the shaping of the shell resulted in low strength as demonstrated by low failure load (38.25% failure load to self-weight compared to 393% for Test Shell 1 and 432% for Test Shell 2 respectively). This is an important lesson in shell design which also emphasised stability of a shell structure. Finite element analysis and actual failure testing highlighted the vulnerability of the shell edge which could be improved by incorporating reinforcements or thickening the edges to strengthen the edges.

Openings were successfully made using *resist impactos* which were designed to be removed easily. However, this needs further refinement.

The following chapter will use a hypothetical construction of the Downland concrete shell to combine lessons learned in previous tests to demonstrate the approach to constructing a concrete shell using a form-found and well-established gridshell as formwork for concrete shell casting.

Detail, Test Shell 4, 2016 (Gabriel Tang)

PART 4 ASSIMILATION AND CONCLUSION

Chapter 10

PROSPECTIVE APPLICATION AND DISCUSSION

Chapter 10: Prospective Application and Discussion

10.1 Aim:

Previous sections discussed the technology, aesthetics and structure associated with the hypothesis when applied to mock-ups and prototyping constructions. Large-scale application has not been tested due to practical reasons. This chapter is a rational analysis of the hypothesis as a solution to construct a large scale structure using this method.

With limited resources and funding, it is not practicable to construct concrete shell buildings at life-scale. Therefore, to objectively assess the viability of constructing concrete shells using deployable gridshells as formwork, this system is carried out speculatively to consider system reusability, reconfigurability and their role as intuitive actively-bent formwork. The chapter is structured as a hypothetical exercise that sought verification from constructional, aesthetic and structural viewpoints to simulate this method of construction objectively. Through this process, issues may be raised to evaluate the possibility of building concrete shells this way.

10.1.1 Construction and Tectonics:

- Is building a structure of a similar scale of Weald and Downland gridshell by using it as formwork possible?
- What are/ might the difficulties of using this technology?
- To what extent can the gridmat be reconfigurable / easily-deployed for re-use?
- Openings (resist impactos) and other options

10.1.2 Aesthetics:

- What is the appearance of the shell from the inside.
- Idea of stereogeneity and expression of gridshell formwork
- surface treatment
- illumination (reflectance material) and ventilation of shell through a qualitative assessment of light quality
- Depth of cushioning and visual interest

10.1.3 Structure:

- How strong is the resultant shell?
- How thin can concrete shells be?
- How does the result compare with other concrete shells?

To test this idea comprehensively, the Weald and Downland Gridshell designed by Edward Cullinan Architects and engineered by Buro Happold is treated as concrete formwork. To discuss issues of construction, tectonic and aesthetics, a concrete shell replicating the Weald and Downland gridshell shape is carried out. To discuss the structural performance of the resultant concrete shell, a digital finite element analysis exercise is carried out.

10.2 Constructing a concrete shell using a Weald and Downland Gridshell shape as formwork.

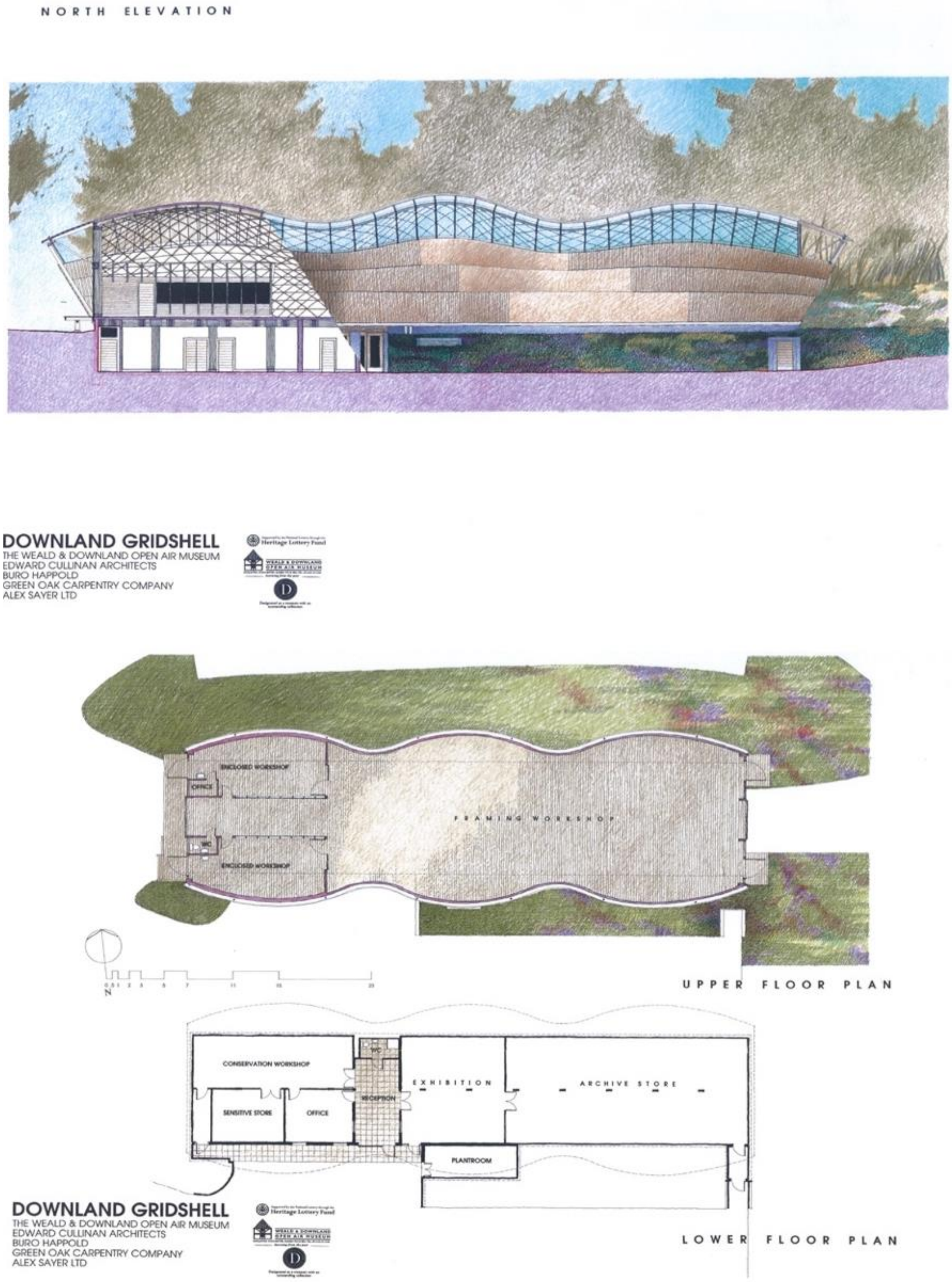


Fig 10.1 Plans, elevations and sections of the Weald and Downland Gridshell, 2002 by Studio Cullinan.

10.2.1 Scale, Morphology and Construction

On plan, the Weald and Downland gridshell measures 50m long, its widest points measuring 16 m decreasing to 12.5m at the narrowest. It has a crest height of 9.5m falling to 7.35m in the valleys. (Harris et al, 2002; Chilton and Tang, 2017). The moderate scale and span, was deemed suitable for the initial trial, demonstration and application of this technology.

Lessons on construction improvements learnt from the 1976 Mannheim Multihalle saw three main improvements being actioned on the Weald and Downland Gridshell:

- Firstly, improvement on bolting connections was made to prevent material weakening by drilling through timber gridlaths resulting in a number of breakages in Mannheim Multihalle.
- In the second instance, the drop down method of gridshell forming at a height through the use of Peri scaffolding systems ensured a safer construction process and one which allowed gravity to guide the deformation, rather than working against it (as was in Mannheim Multihalle).
- Thirdly, the shape of Weald and Downland gridshell was the result of reiterative form-finding by Chris Williams at the University of Bath which is improved from the Japan Pavilion paper-tube gridshell in 2000.

In using the formfound shape of Weald and Downland gridshell, two main concerns are ensured: Firstly, that the gridshell formwork is deployable, and the construction process is established and works. Secondly, an efficient gridshell shape, through historical form-finding reiteration was guaranteed.

In this exercise, form-finding is not the main objective. The main purpose and aims of this exercise is extensively outlined in Chapter 10.1 and as a summary, concerned with the construction, aesthetic and structure.

Project Construction of the actual timber gridshell

In the Weald and Downland gridshell, pre-joined laths of Normandy oak were laid in one direction and then another cross laid on top. The gridshell was formed from four layers of oak timbers 50mm x 35mm deep sections. To span long distances, laths were attached with special patented clamps which enabled sufficiently loose intersecting rotations to take place (for details, refer to Chapter 5.4.1.2). The process took a period of six months for the gridmat to be manipulated into the final form from an elevated level. Extensive use of PERI props were used to gradually lower the grid-mat at each point to form the gridshell. The shape of the eventual timber gridshell was a triple bulb shape.

Fig 10.2 Stages of timber laths being deployed from height starting with a flat mat.

Fig 10.3 Clearly shows the illumination of interior space offered by the two bands of polycarbonate cladding

10.2.2 Openings and illumination

In the Weald and Downland timber gridshell, two strips of polycarbonate strip clearstories allowed light to enter the space which it enclosed (fig. 10.3). Tectonically, the functions of structure (gridshell) and cladding (skin) is clear. The flanking clerestory windows were the result of addressing one of the key challenges that gridshells experience - the question of enclosing a three-dimensional shape using a two-dimensional material (Chilton and Tang, 2017). The solution consisted of a roofcrete "ribbon" that followed the ridge of the triple-bulb and accompanied both sides by polycarbonate panels, throwing light into the space beneath. This solves the problem well, although the expressive double-curved, triple-bulbed gridshell is hidden within a cloak of timber, plastic and concrete and is not seen on the outside.

The treatment of window clerestories produces a pleasant quality of top light conducive to woodworking courses. To replicate a similar clerestory banding when constructing a concrete shell version will not be congruent to this proposed method of construction i.e. casting concrete shells on a temporarily strained gridshell, but would interfere with the structural function of the shell as demonstrated by Eladio Dieste’s strip lighting along force lines in the salt silo in Montevideo (fig. 9.12). Window openings placed across shell forcelines should be avoided as demonstrated by the designs of Kimbell Museum (Louis Kahn 1972) which required engineering corrections to realize

Kahn's original vision. Although the requirement of top light is fulfilled, the openings in concrete shell cast onto gridshells as formwork should be treated differently and be expressed sensitively, and be informed by the construction, aesthetics and structural considerations.

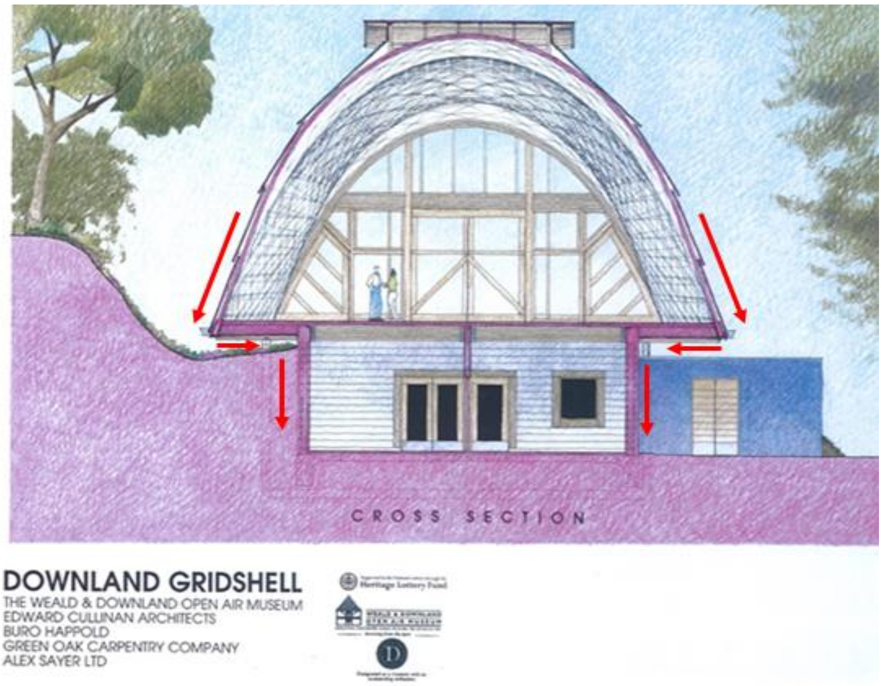


Fig 10.4 Existing timber gridshell transfers load and stabilized by a floating timber floor that transfers load onto the concrete plinth.

10.2.3 Meeting the ground and transferring load to the ground

The Downland timber gridshell "hovers" above ground. With the new shell constructed out of concrete, unless the timber floor is designed to bear the weight of the concrete shell, a timber transfer beam should be avoided (fig 10.4). Instead, the thrust of the shell is designed to transfer directly into the ground. The new proposed concrete shell is envisaged to extend towards the ground with Y-shaped columns similar to the load transfer treatment of Palazetto dello Sport (Luigi Nervi, 1960) on this specific site. Concrete loads are picked up by these special columns that extend the geodesic lines to the ground (fig. 10.11 and 10.14) in the way Luigi Nervi's columns at Palazetto dello Sport's Y shaped columns (fig 10.5).

Fig 10.5 Y-concrete columns transfer load of the shell into the ground.

10.2.4 Repeatability and deployability

On plan, the gridshell is identical as three sections as each is a bulbous shape. The behaviour of deployable gridshells is applied here to take advantage of their ability to deploy. To construct the concrete shell using repeated and reused gridmat, it will be constructed in three phases. It is imagined that the same gridmat for each bulb will be collapsed and elongated to form a lattice tube for manoeuvrability (fig 10.8). The ends will be attached to inflatable air-forms that will raise the gridshell into pre-determined distances on the edges and also heights.

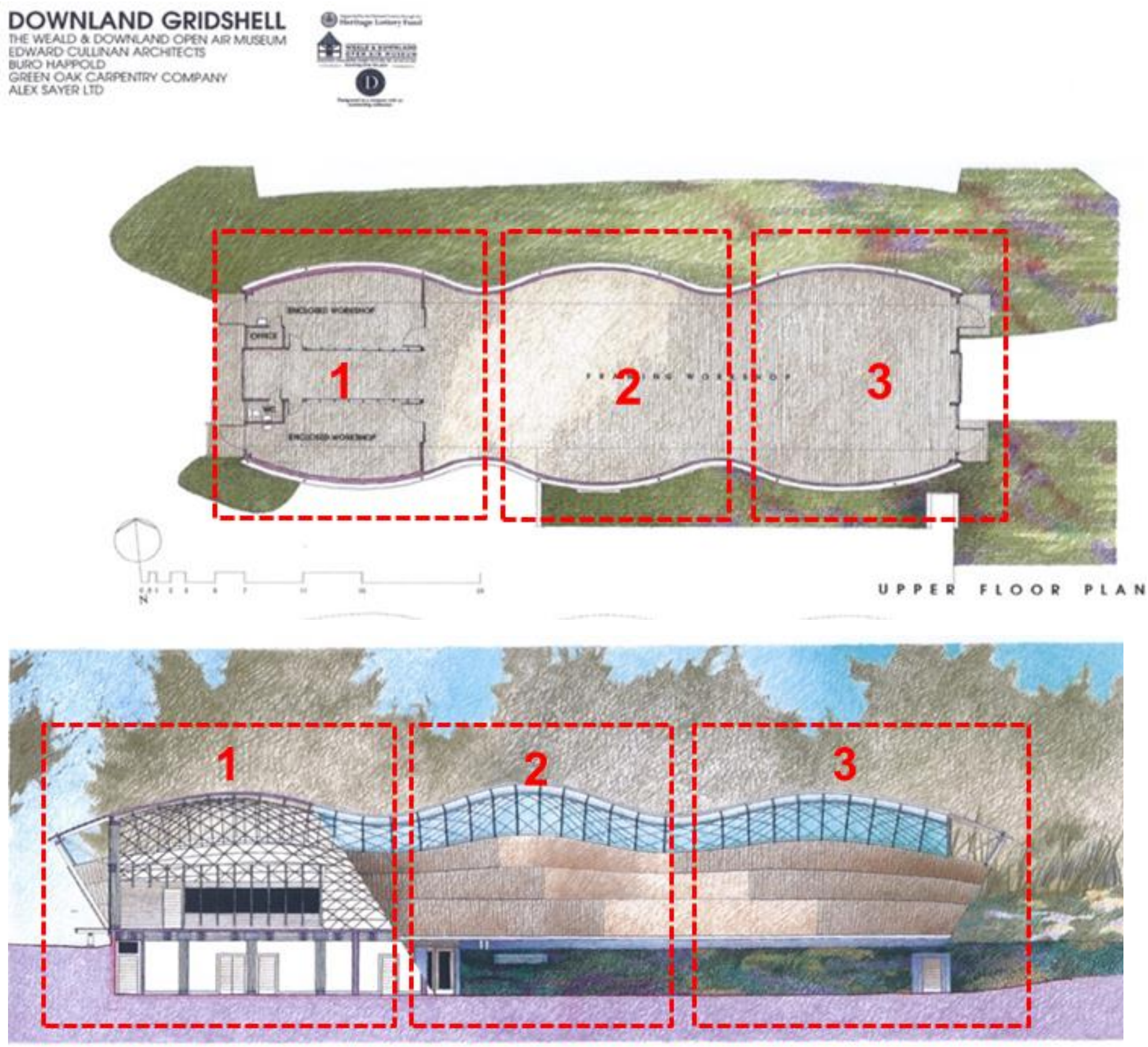


Fig 10.6 Existing timber gridshell transfers load and stabilized by a floating timber floor that transfers load onto the concrete plinth.

The system is used to build a triple-bulb gridshell using a third of the deployed gridshell as formwork.

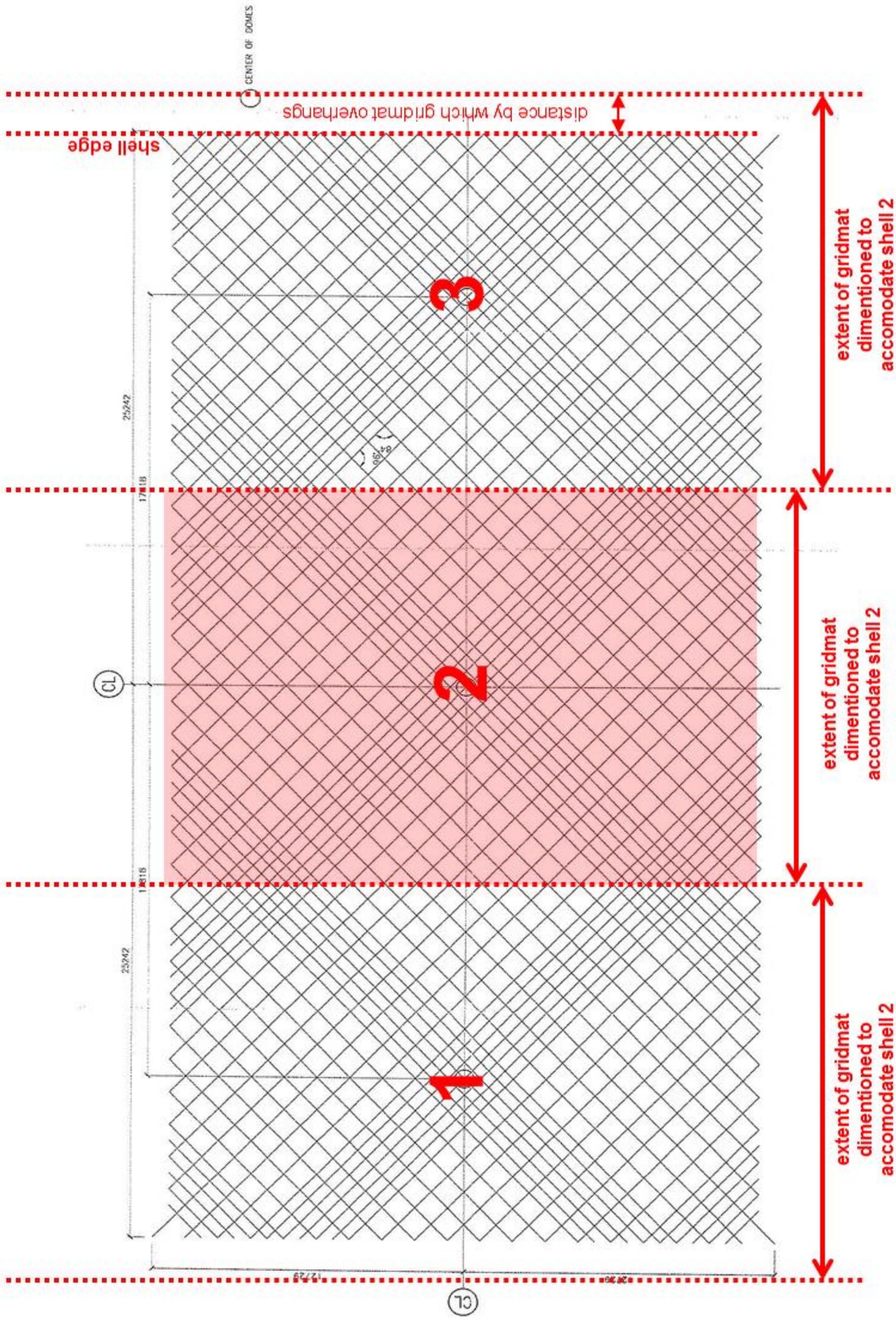


Fig 10.7 Plan of gridmat is divided into 3 narrower sections. It is observed that although tri-bulbous, the middle section is found to be wider than the flanking bulbs. The mat must therefore be made to the dimension of shell 2. When sections 1 and 3 are cast, the edges will terminate before the edges of gridmat formwork terminates (similar to test shell 4 free edge).

Upon close study of the construction drawing of the gridmat pattern (courtesy of Studio Cullinan, London), although the gridshell was tri-bulbous, the gridmat that formed each bulb were not identical. Fig 10.7 portrays the construction gridmat patterning. It is divided into three sections 1, 2 and 3 as drawn, with section 2 describing the middle bulb. It is noticed that middle section 2 is actually wider than flanking sections 1 and 3. Therefore, to construct the gridshell using one single deployable mat, it is necessary to form gridmat 2, re-use and cast sections 1 and 3, bringing termination of shell edge backwards with a margin.

Similar to the construction of the actual Weald and Downland gridshell, the datum points set by the centre-lines of each of the bulbs must be determined and set. The termination at both edges of shell 2, inscribed by the gridshell formwork will be useful to locate where the gridshell formwork can continue from.

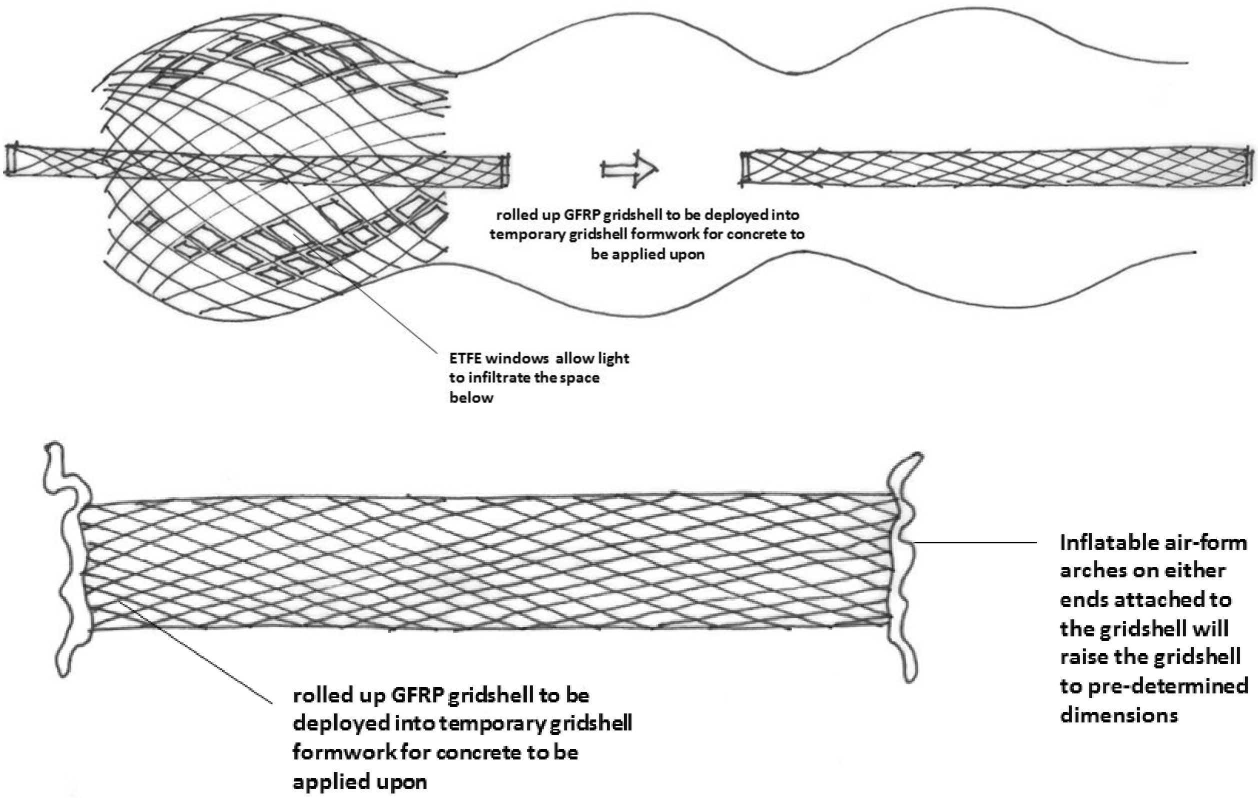


Fig 10.8 Principles of deploying and reusing formwork for casting.

In this proposal, the construction of the gridshell formwork gridmat would be brought to site as a double layered pre-made GFRP lattice with swivel connections similar to that used in Creteil gridshell rolled up like a cigar tube. As elastic deformation for a GFRP gridshell can be completed relatively quickly (the 280m2 Solidays gridshell took a period of 10 hours to construct (Tayeb, F., Baverel, O., Caron, J. F., & Du Peloux, 2013)), the use of Peri scaffolding system may not be necessary. To deploy the gridmat, a pneumatic system is imagined. Each edge of the gridshell is attached to an inflatable air-form pneumatic arch pre-made to accurate dimensions and attached to the gridmat. The respective ends of the gridmat will be attached to these separately and reinforcement bars will be embedded within the concrete.

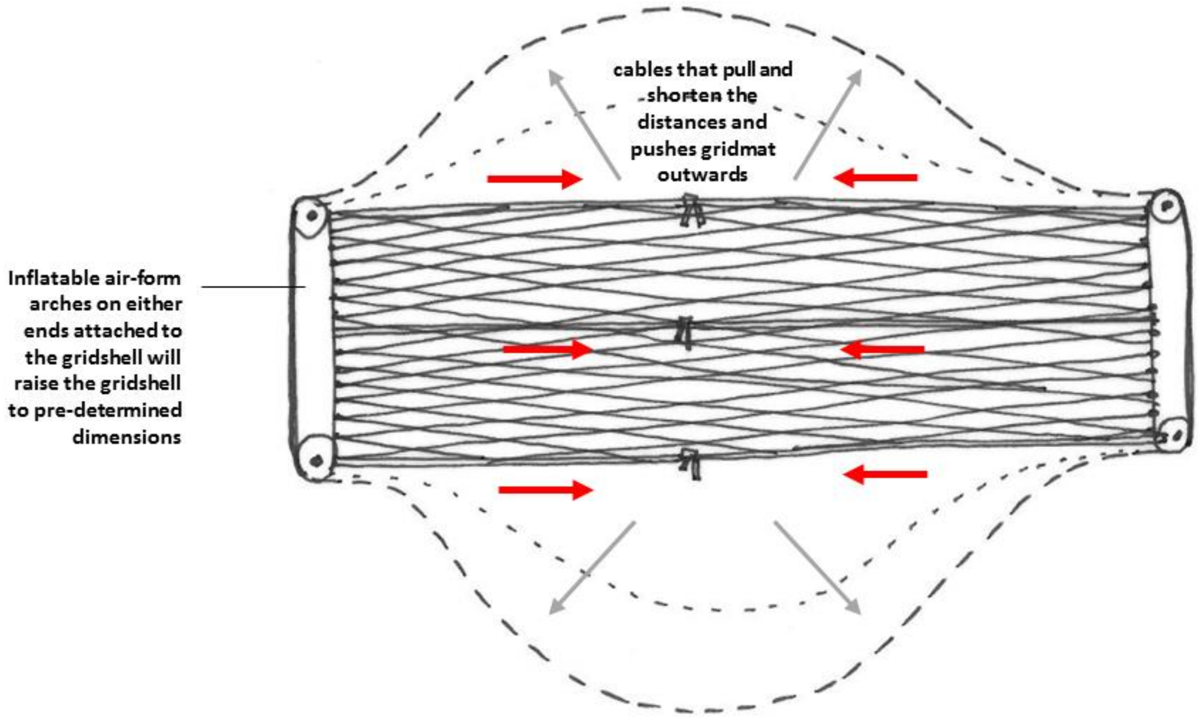


Fig 10.9 tubular gridshell formwork flares out deployed through the effect of shortening steel cables that connect the opposite edges of the gridmat together. Bracing sections will be added afterwards to provide in plane rigidity whilst the concrete is being applied.

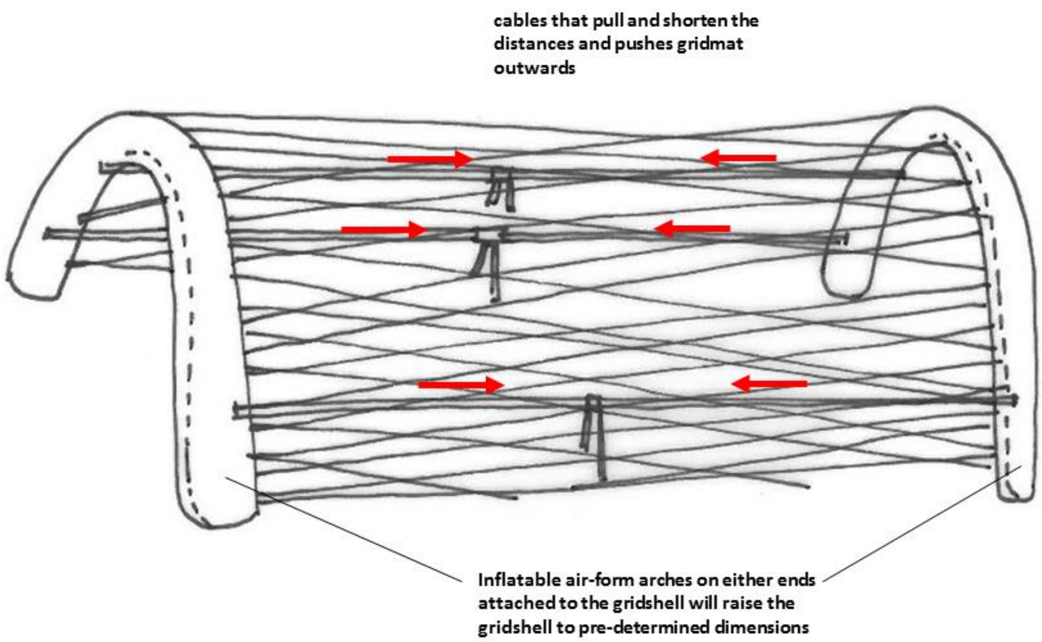


Fig 10.10 Principles of deploying and reusing formwork for casting.

To erect the gridmat, two pneumatic arches are inflated. Once inflated, steel cables are attached to the gridmat edges. When these cables are shortened, the arches are pulled towards each other. Tensioning would cause the gridmat to deploy, flare up and expand to produce shell with approximate curvatures.

The same GFRP tubes will be used as bracing to stabilize and rigidify the shell. These will be connected using swivelling scaffolding joints used by Baverel at Cretail, 2012 (Tayeb, F., Baverel, O., Caron, J. F., & Du Peloux, 2013).

The adjustment and fine-tuning of the gridshell to accurate curvatures can be achieved in two ways: firstly, by ensuring the bracing distances (i.e. distances between triangles) are accurate to designed distances. Temporary triangulating bracing with pre-calculated distances can be applied to rigidify the gridshell. This will offer the opportunity to create designed double curvatures by the opportunity to pull together or push apart the gridmat to induce desired synclastic or anticlastic curvatures. Secondly, vertical distances need to be monitored to match designed heights at specific gridmat intersection points similar to the way the vertical distances of points from the ground datum, possibly with a laser tape measure. If necessary, the deformed gridmat may also need to be propped up with vertical columns for control and stability during gunniting similar to propping used to support and check heights of key points (as used in Test 3). This will be described further in Chapter 10.8.2.

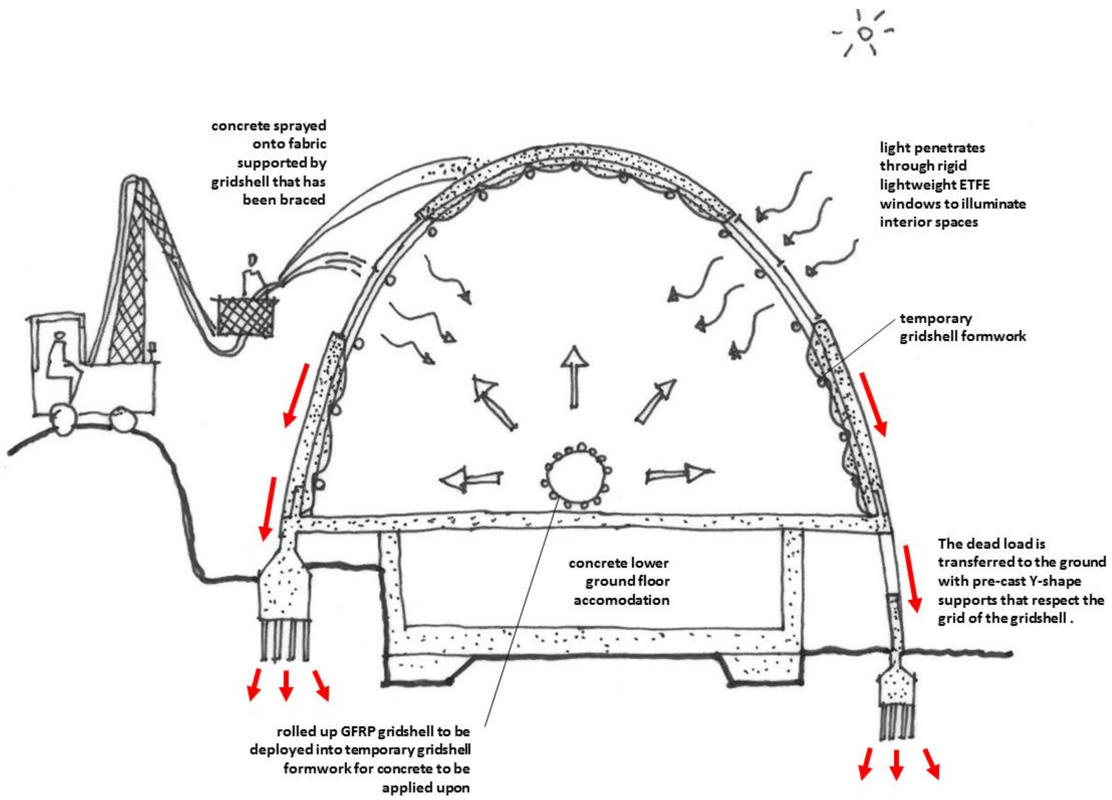


Fig 10.11 Section of possible concrete shell construction

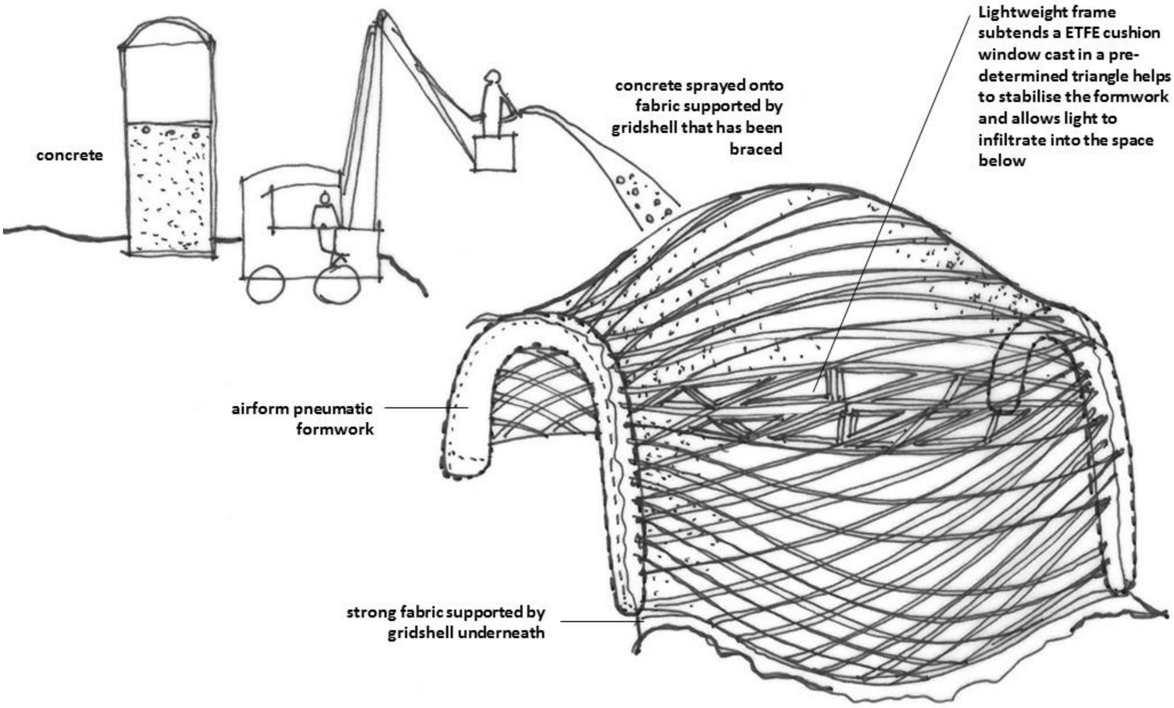


Fig 10.12 Spray applied onto gridshell formwork supported with air-form inflated arches at ends.

10.2.5 Fabric Formwork Cover

When the gridshell reaches the desired geometry, through triangulating bracing, the entire shell can be covered with a fabric transversely. With the fabric stretched taught and without creases, the edge beams elements produce an edge detail (demonstrated in Test Shell 4) can be connected. To check for a consistency of thickness, the thickness stubs of the desired depth can be attached (also demonstrated in Test shell 4).

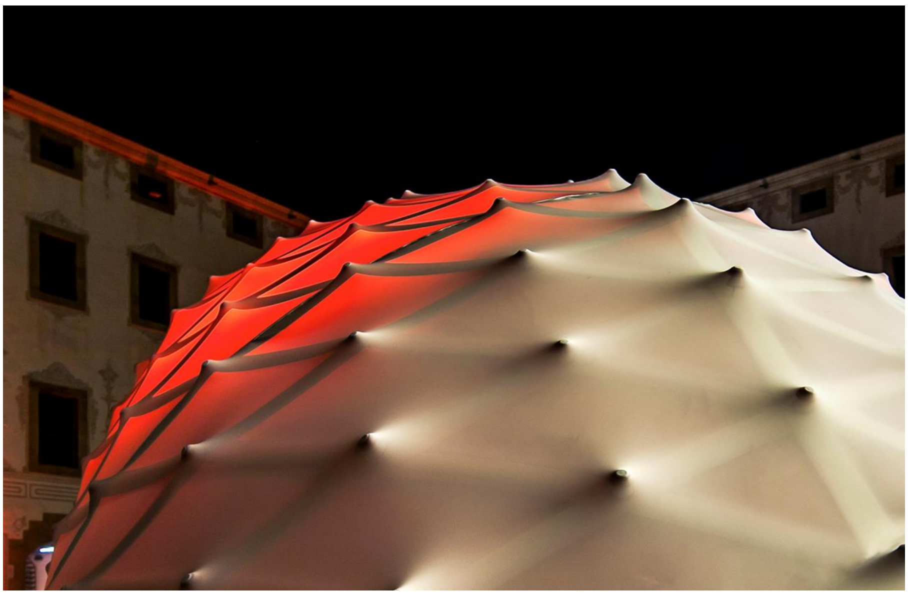


Fig 10.13 Unpatterned membrane stretched over a gridshell made from GFRP Planks.
http://coda-office.com/work/Labsis

10.2.6 Edge Treatment

With guidance from structural engineering advice, it may be necessary/ advisable to incorporate reinforcement bars/ mesh within the shell. Learning from the failure test behaviour from Test 4 which showed first fissures during failure testing, it is deemed good practice for rebar embedded within the open edges in sections 1 and 3 in this construction exercise.

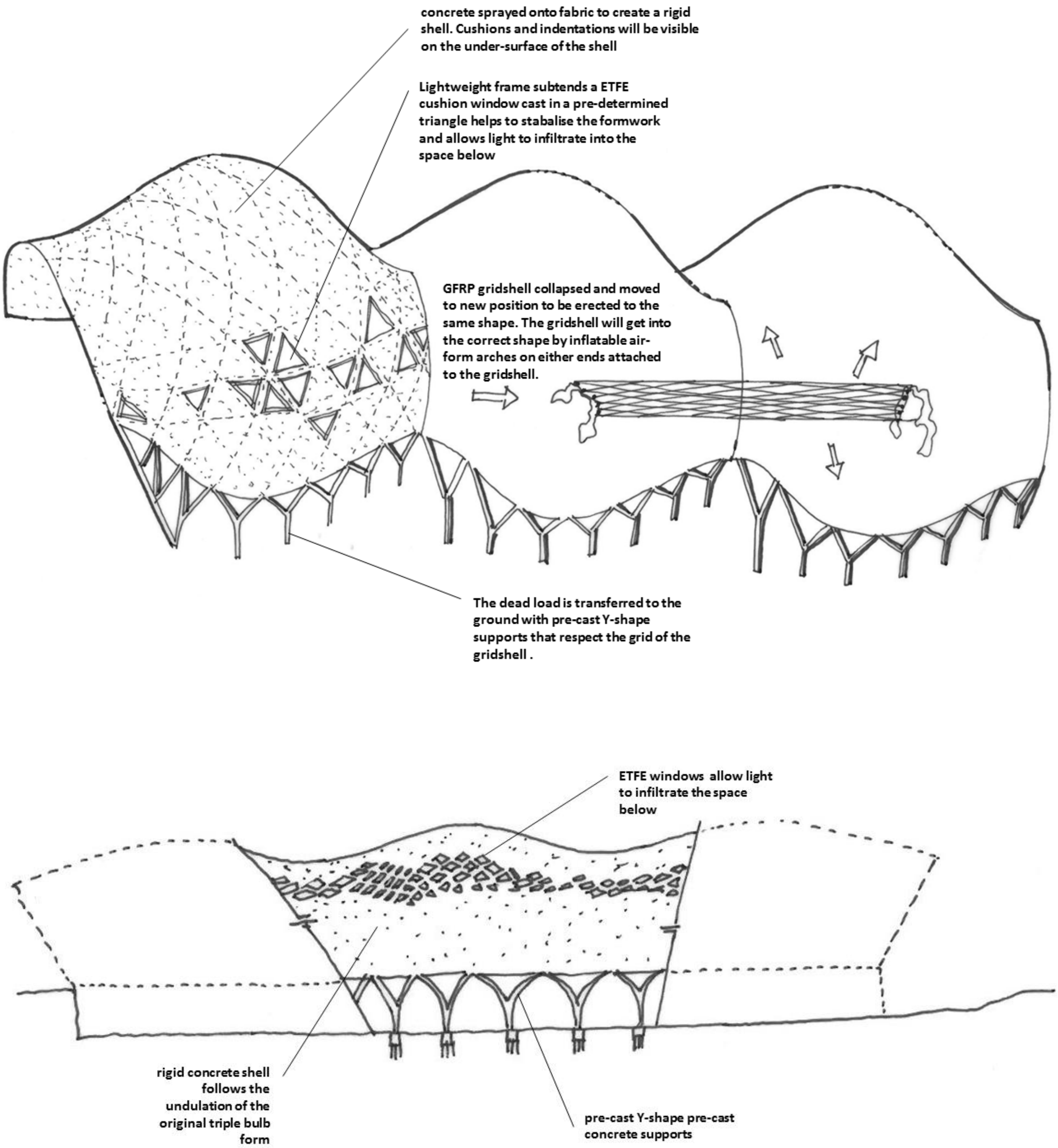


Fig 10.14 top: Repetitive Concrete Casting in sequential construction
bottom: Elevation of possible resultant concrete shell

10.2.7 Openings

The openings are formed by *resist impactos* created in the same principle as carried out in test shell 4. Lightweight foam will be attached into the grid frame after fabric is attached. Using computer aided design CAD software packages, the exact sizes and dimensions of the openings could be determined and be made from polystyrene foam which are pre-cut to diagrids dimensions or triangles that could be inserted into specific grid spaces/ locations. When installed, these *resist impactos* would also provide shear stiffness, in addition to triangulation (similar to plywood installed to the Savill gridshell as discussed in chapter 5.4.1.3 to rigidify the structural form which through test shells 1, 2, 3 and 4, have proven to be important challenges to maintain rigidity from casting movements.

10.2.8 Casting method: Sprayed concrete

Due to the large surface area, the entire shell will have concrete sprayed by sprayed concrete specialist. The concrete mix will need to be adjusted to suit the inclinations of the surfaces to prevent rebound and wastage. If required, concrete should be sprayed on in multiple layers.

During discussions with Bill Jones, president of the Sprayed Concrete Association, UK (Jones, 2016), the confidence of using this technology was clear. Two key considerations need to be taken into account. Firstly, the use of a dry mix is recommended to be used in this scenario as surfaces describe steep gradients and dry mix allows concrete to better adhere to the surfaces. Secondly, to achieve smooth surface finishes, the concrete may need to be trowelled and smoothened afterwards. The finishing surface in question is on the upper and outer surface of the completed concrete shell which may be further cladded with a material suitable to the climate in question, or like Candela's shells, be smoothened and painted. Sprayed concrete had been used more recently as a constructional solution to create the “Cacoon” at the Darwin Centre in London. Designed by CF Moeller, the new extension to the Natural History museum consisted of an eight storey tall curved structure containing museum spaces.

To construct this structure, a sixty-five metre long skeletal Cacoon was constructed by spraying concrete 300mm to 425mm thick (Philips and Yamashita, 2012) onto a sacrificial framework of steel re-bar frame covered by expanded metal mesh to create concrete walls, ivory coloured finishing plaster with thermal stability to be used for the 3,500 m2 raw concrete surface (Marine Aggregates website assessed 20/06/17). The use of dry mix was used in this case and adhered well to the vertical sides.

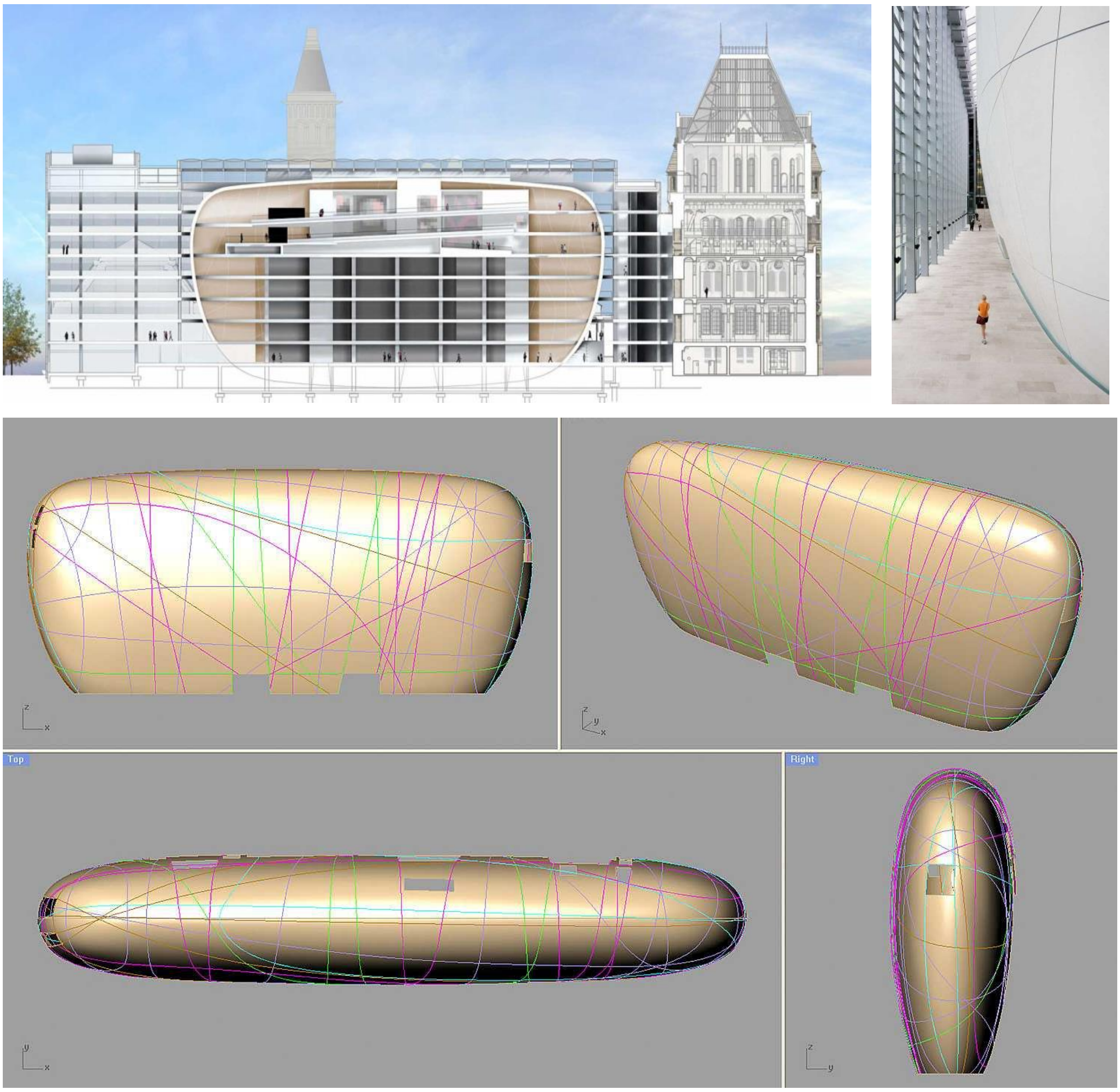


Fig 10.15 The 3500 m2 surfaced cacoon, designed by CF Moeller, 2009) is constructed by spraying concrete onto an expanded metal mesh backing supported on a re-bar structural framing. (images courtesy of CF Moeller)

Spraying concrete onto gridshell formwork, to control layers of the shell, small vertical guides may also be affixed onto the grid-frame, similar to metal stubs for the test shell 3 to monitor concrete evenness. With confirmations from engineers, a matrix of steel reinforcement may need to be installed to fortify the structure and give it additional strength, stiffness and as precaution to cracking. Steel mesh was embedded within the shells of Eladio Dieste, Candela and Heinz Isler too. They were largely functioning as a precautionary measure as their shells are largely efficient.

10.2.9 Model making

The primary aim of the construction of the 1:20 scale model of the Weald and Downland Gridshell model is to simulate the construction of the scale at full scale. The exercise will raise concerns and issues concentrating on aspects on construction of the gridshell formwork, concrete casting, decentring. The resultant concrete shell replica is also useful in assessing aesthetic issues. The model will give a good indication of the quality of spaces enclosed by a shell constructed from this technology.

Specifically, the making of the model simulates the actual construction process to address the points below:

10.2.10 Construction and Tectonics:

- Is building a structure of a similar scale of Weald and Downland gridshell by using it as formwork possible?
- What are the difficulties of using this technology?
- To what extent can the gridmat be reconfigurable / easily-deployed for re-use?
- Abutments
- Edge conditions and details: free edge and abutments.
- Openings (*resist impactos*) and other options

10.2.11 Aesthetics:

- What is the appearance of the shell from the inside.
- Idea of Stereogeneity and expression of falsework.
- Surface treatment
- Illumination (reflectance material) and ventilation of shell through a qualitative assessment of light quality
- Depth of cushioning and visual interest

10.3 Test construction of a 1:20 Scale Model

10.3.1 Materials:

- 2mm diameter GFRP rods
- plastic cable ties
- 18mm mdf baseboards
- 2mm steel staples
- Plaster infused bandages
- Plaster of Paris
- 5mm foam boards

10.3.2 Constructing gridshell

Construction drawings courtesy of Studio Cullinan depicted the arrangement of timber laths on plans and the eventual timber gridshell heights.

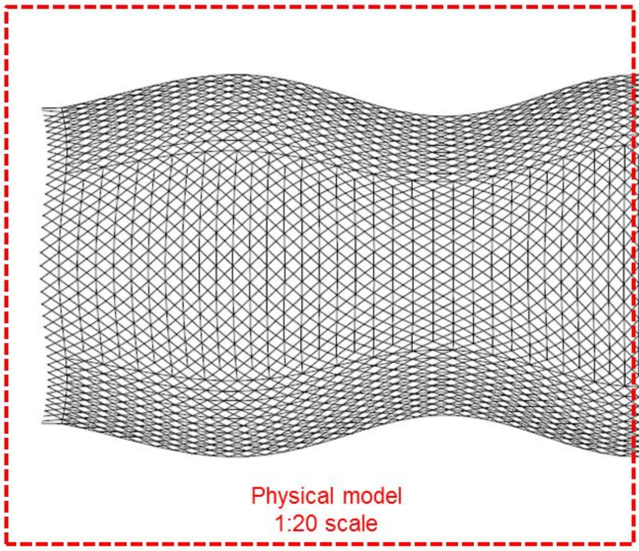


Fig 10.16 shows the extend of the physical model of the gridshell formwork to be constructed from 2mm intersecting GFRP rods.

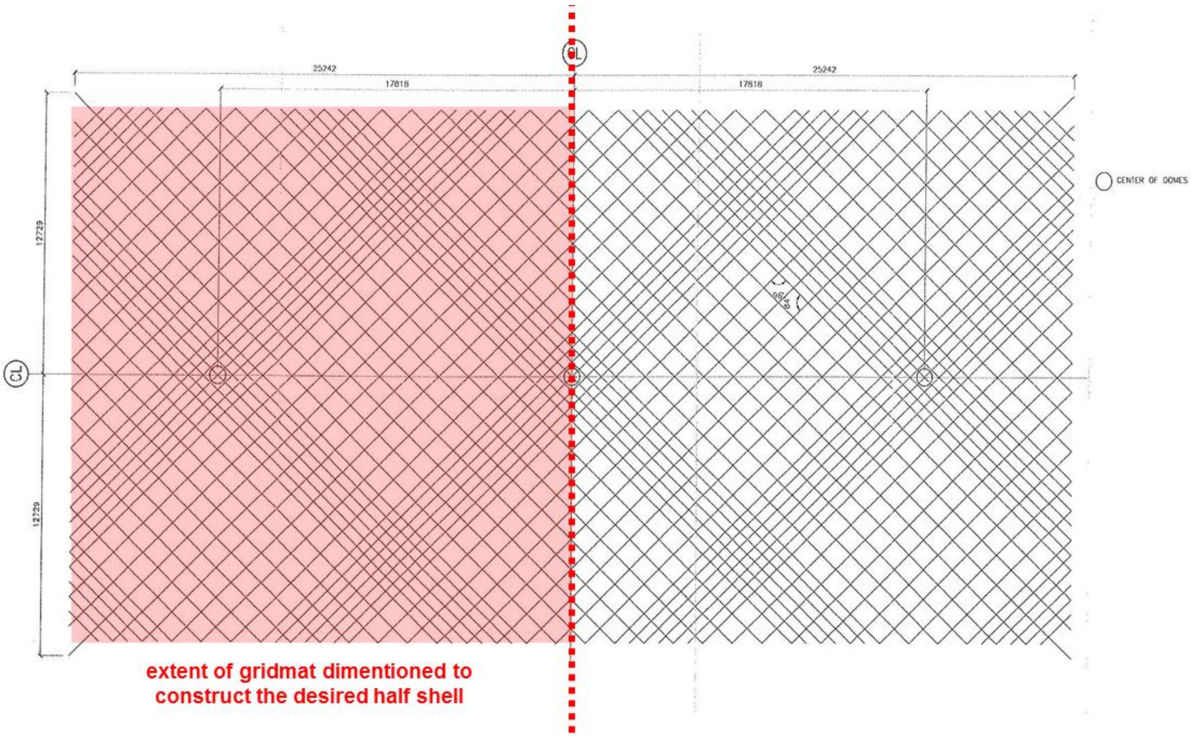


Fig 10.17 shows the extent of the physical model of the gridshell formwork to be constructed from 2mm intersecting GFRP rods.

The rationale to create half a shell rather than a third, which would be repeated twice more to create the triple bulbous shape as suggested by earlier section on repeat-ability and re-usability was based on the limitations of the scaled model. The flexibility of the model GFRP gridmat and scale of the construction including the filigree joining of the grid-laths would not give a true reflection of the actual construction. As such, this exercise focusses on the fabrication of gridshell formwork, casting of shells with openings and the subsequent decentring, as well as assessing the aesthetic of the space created within the shell.

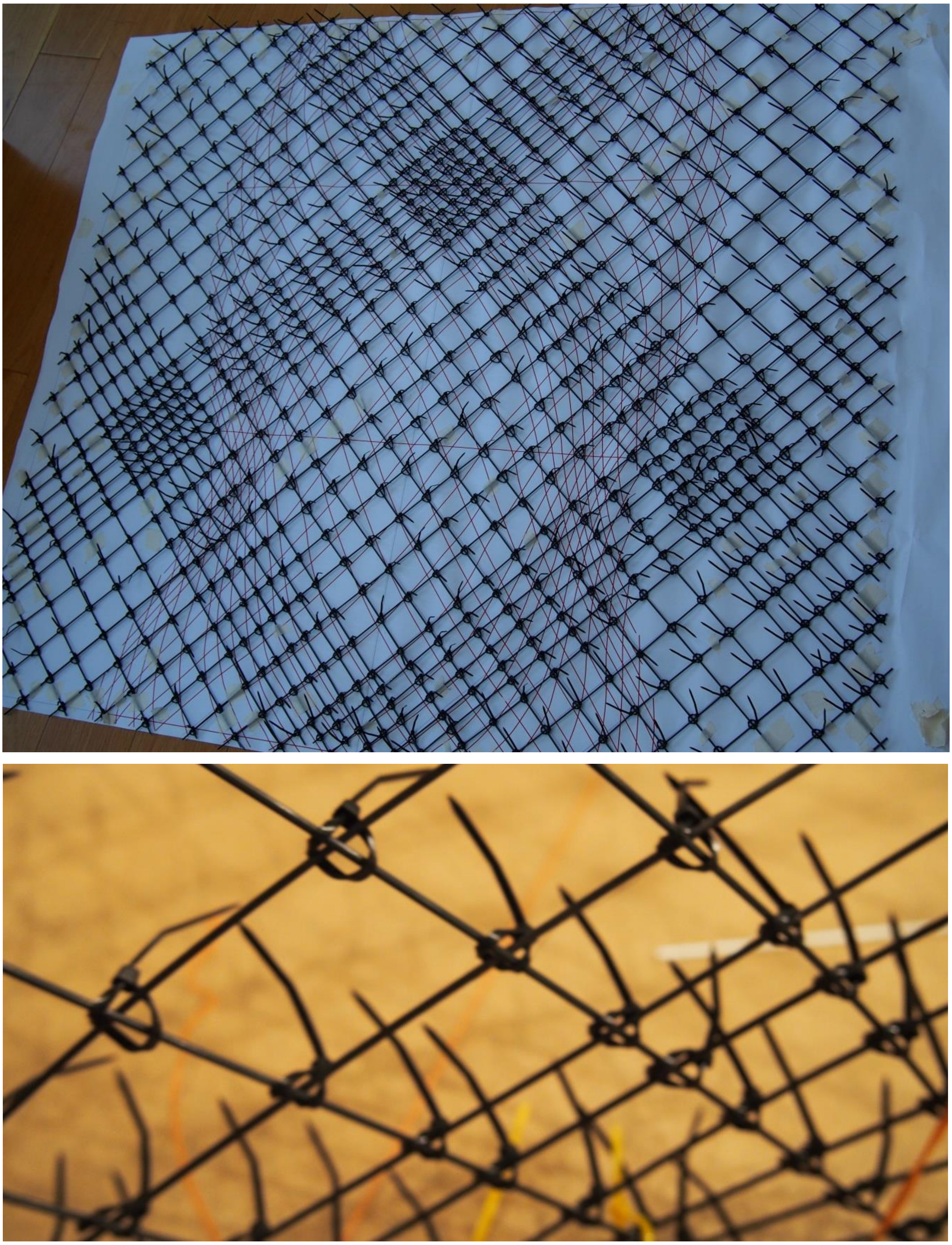


Fig 10.18 (top) by cutting laths of GFRP rods into suitable lengths, the gridmat is formed to follow the pattern for creating half a shell. Rotating intersections are created by tying cross laths using one single cable tie at each intersecting node.

For the 1:20 scale model, due to shell symmetry, one half of the shell was constructed by attaching 2mm GFRP rods cross members with rotational joints using 100mm long 2mm wide cable ties depicted in figure 10.18.

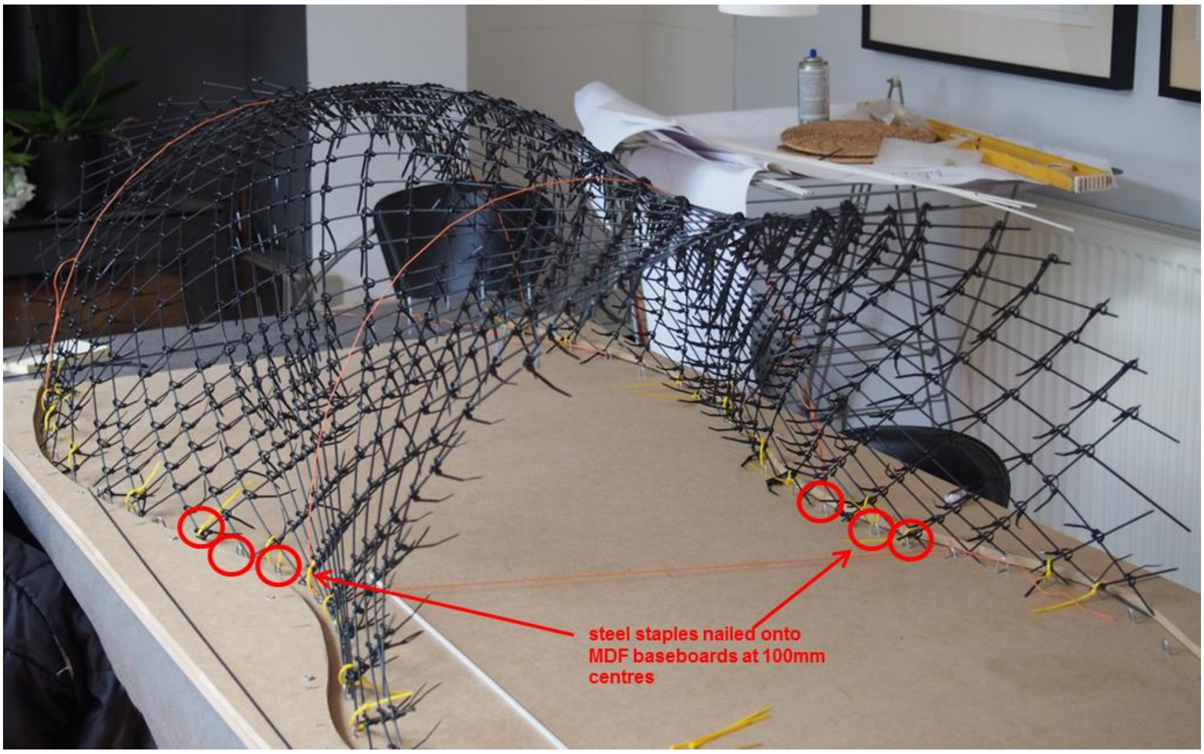


Fig 10.19 Gridshell is attached onto the baseboards by steel staples nailed into the baseboard at 100mm centres

The base of the test was prepared by cutting out the profile of the plan. This ensured a stepped detail in the profile of the model to restrain the gridshell after the gridshell is cast, enables the process of decentring to take place easily and allow the deployed gridmat to be removed easily.

Once the gridmat was erected and tensioned between the restraining mdf bases, they are fixed into position first by nailing steel staples onto the mdf baseboards at approximately 100mm centres along the curved outline but on the lower step. The gridmat was then tied back to the baseboards by cable ties seen in fig 10.19. To brace the structure, string was used to the structure and triangulates it. The gridshell achieved the geometry of the form-found gridshell in the apex of the shell i.e. point B in fig. 10.20. To ensure the shell was accurate to the dimensions of the Downland gridshell, a quick checking measurement of points A, B, and C heights of the shells e.g. the apex and valleys of shells, showed measurements deviated 10mm (i.e. 200mm deviation in the actual dimensions) from the (scaled) designed heights. This was attributed to the efficient shape form-found by Chris Williams. However, the deviation at point D was very pronounced. In fact, the shell did not achieve the desired shape ie one half of the bulb. This suggests that the division of the mat into 3 sections edging at the valleys will achieve the continuation of the shell. This implies that to rationalise and section the shell into different reusable gridmats, care must be given to ensure edge lines should ideally matching up the lowest points ie valleys of the complete shell structure.

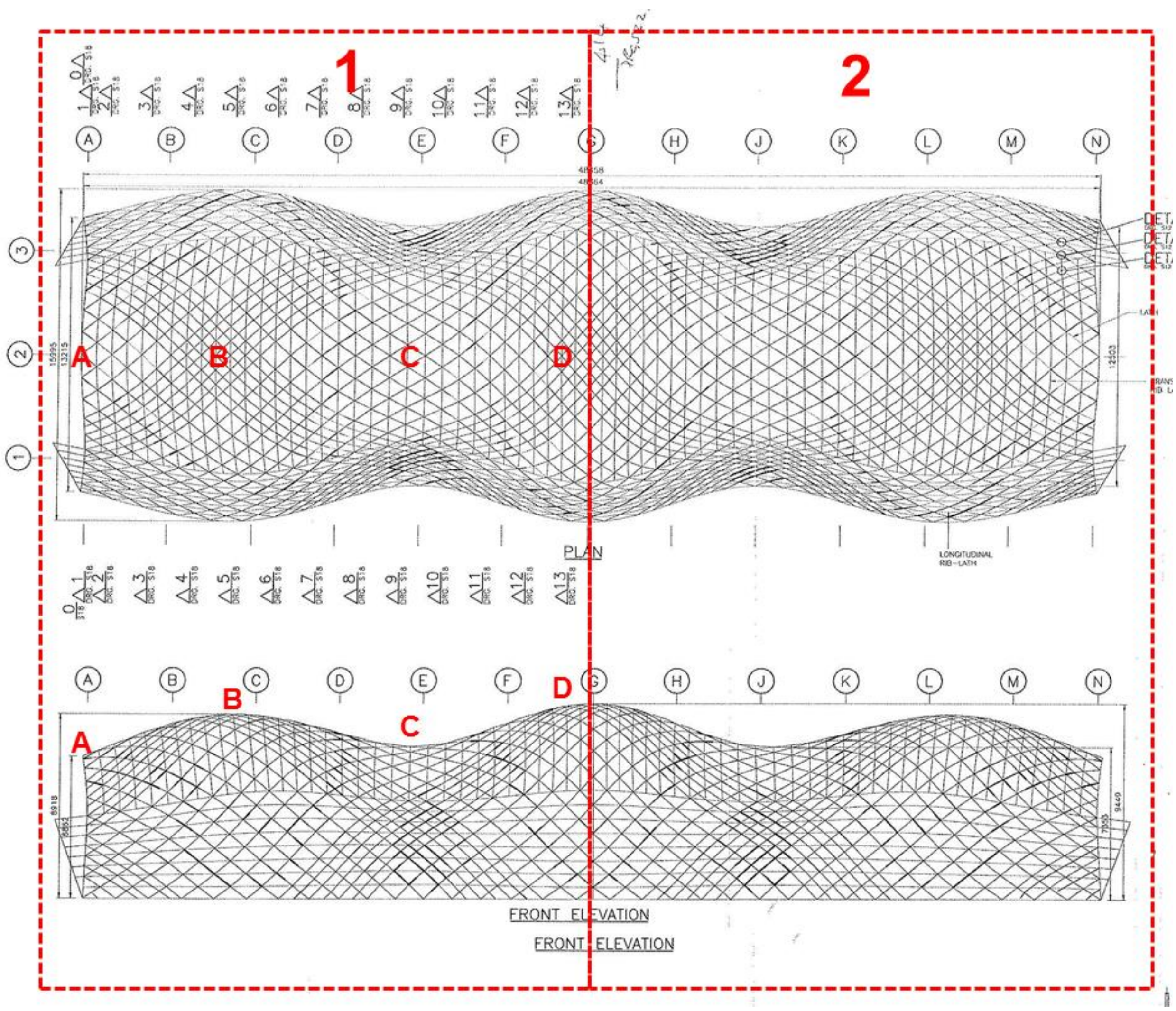


Fig 10.20 shows the extend of the physical model of the gridshell formwork to be constructed from 2mm intersecting GFRP rods

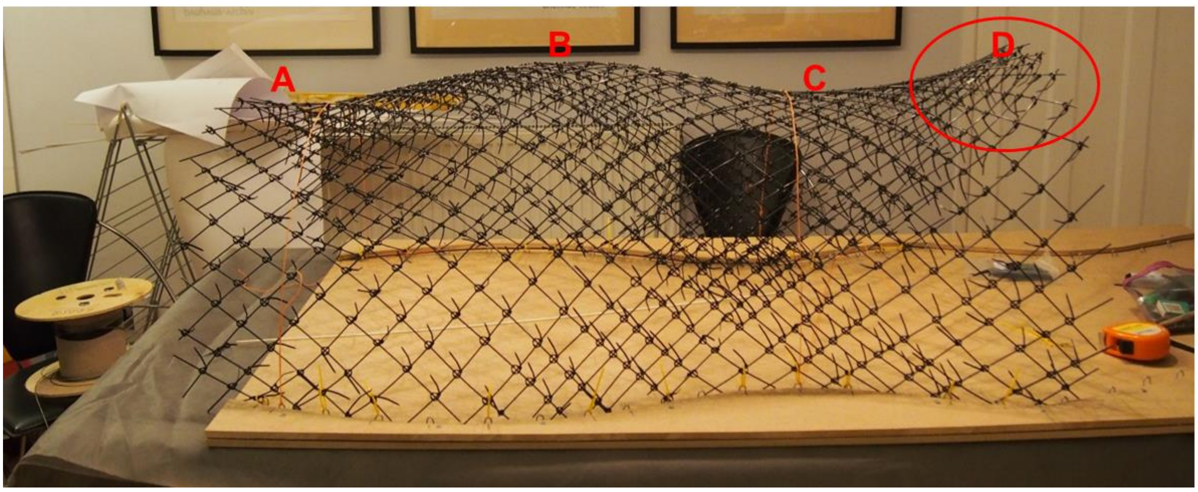
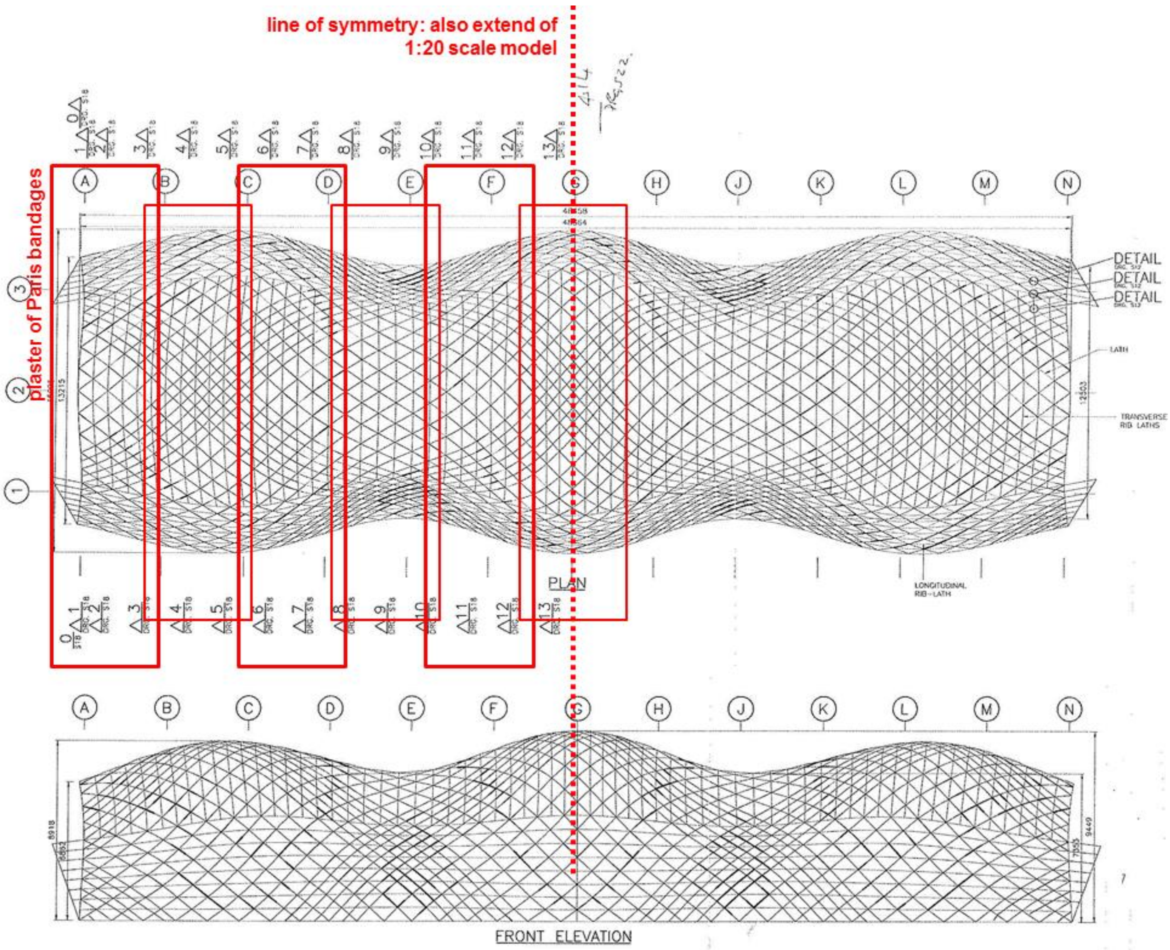


Fig 10.21 shows the extend of the physical model of the gridshell formwork to be constructed from 2mm intersecting GFRP rods

10.3.3 Casting the Shell

Plaster is used to replicate concrete in this exercise. Instead of using a fabric as formwork, Modroc plaster of Paris Modelling bandages 210mm wide were laid transversely across and onto the gridshell formwork suggested by fig 10.22.



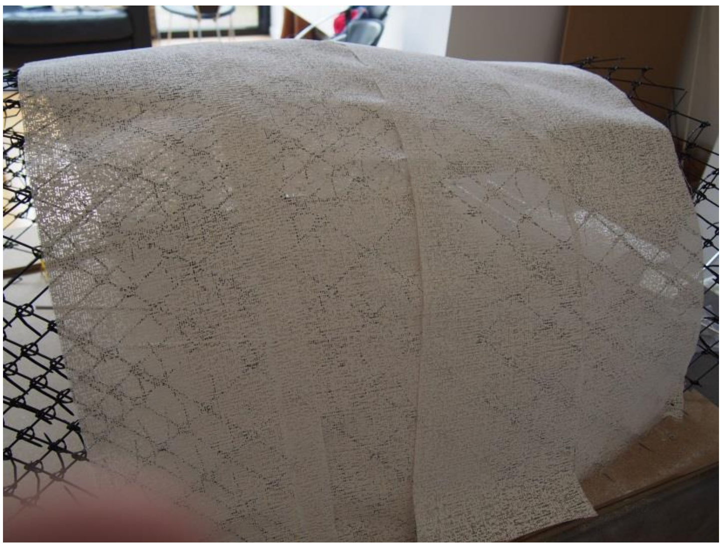


Fig 10.22 shows the extend of the physical model of the gridshell formwork to be constructed from 2mm intersecting GFRP rods

The bandages were then dipped in water to become workable and laid onto the gridshell formwork. It developed rigidity when the entire gridshell was covered. The fabric was stretched tightly to ensure no excess fabric festooned between the grids. When the thin 2 mm layer of material dried, the shell appeared transparent and delicately thin and filigree. The question about scale would be significant when this is constructed at life-scale. Fabric jointing and stretching system presents an important avenue of exploration.

Fig 10.23 The extend of the physical model of the gridshell formwork to be constructed from 2mm intersecting GFRP rods.

10.3.4 Openings: *Resist Impactos*

Lenticular *Resist Impactos* are made from simple 5mm foamboards to form the openings. These are attached onto the thin fabric shell by pins from the upperside and another one from the underside to secure pins.

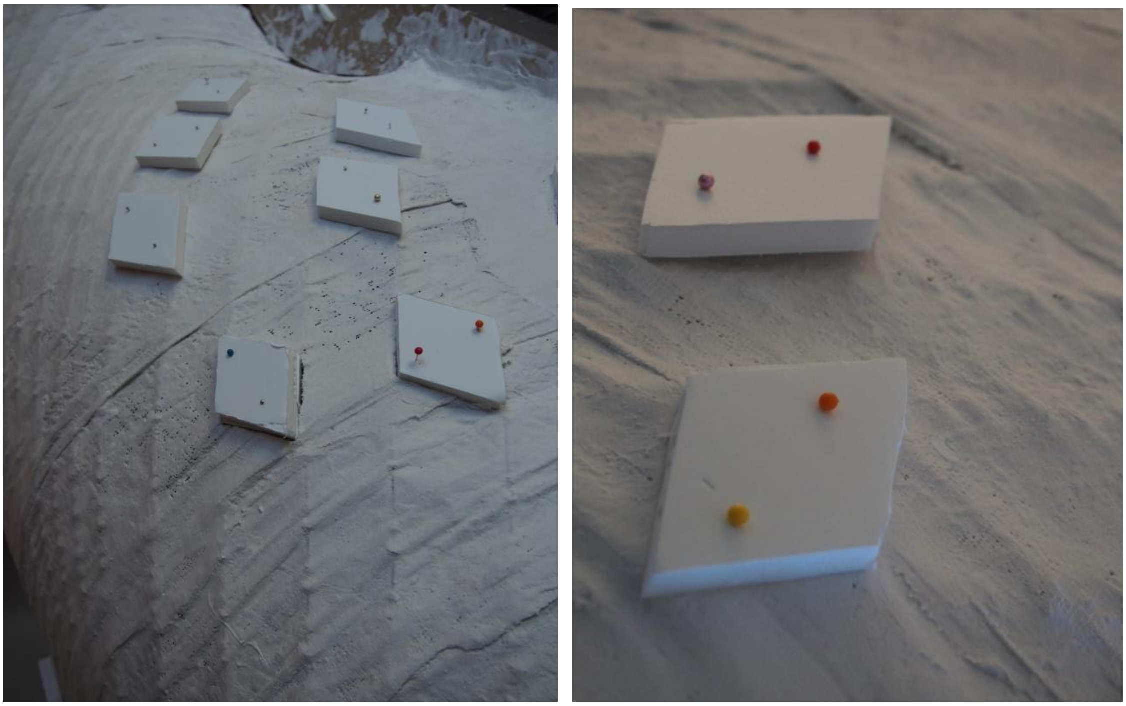


Fig 10.24 shows the extend of the physical model of the gridshell formwork to be constructed from 2mm intersecting GFRP rods.

Fig 10.25 shows the extend of the physical model of the gridshell formwork to be constructed from 2mm intersecting glass reinforced plastic rods.

Fig 10.26 The dia-grid glass panels of the Prada flagship store at Aoyama Tokyo by Herzog and Meuron, 2003, is clad with diagrid glass blocks which follows the structure of the steel-framed building. The diagrid suggests a similar scale to the diagrids of the Downland gridshell of 1m by 1m. Each *resist impacto* could be pre-made to precise dimension, and attached onto the gridshell to create openings within the shell itself. Live loading and temporary support may be necessary to support the heavy glass windows. This may mean that the scaffolding holding up the windows can also act as prop/ checks for the entire shell to ensure the entire structure maintains the required curvatures and do not experience excessive deflection whilst concrete is cast onto the deployed gridshell formwork. An alternative is to create these *resist impactos* by using ETFE instead of glass to reduce load. (image courtesy of Adrian Wiggins)

Fig 10.27 A layer of plaster with reinforcement is trowelled onto the bandaged surface.

When *resist impactos* are in place, a layer of rendering plaster reinforced with polypropylene fibres was applied over this surface with the help of a small hand trowel to an approximate layer of 5mm i.e. until they are level with the *resist impactos*. The shell is gaining stiffness as the shell thickens.

This was allowed to dry and cure for 4 days before 2 layers of diluted plaster of Paris mixed at a plaster to water ratio of 1:8 was painted onto the surface to build up the layers. At each painted layer, the shell was allowed to dry and cure for 24 hours.

Following the completion of the shell, *resist impactos* were removed to create openings which allowed light and air to penetrate into the internal space.

Fig 10.28 Exterior and interior views of the concrete shell.

Fig 10.29 Decentring was completed quickly.

10.3.5 Decentring

Firstly, string bracing that helped to triangulate and brace the structure was removed. Following that, cable ties that connected the gridmat to the ground (base board) were cut. The gridshell formwork detached itself easily from the concrete shell itself and was collapsed and removed.

10.3.6 The resultant concrete shell

The resultant concrete shell bore the impressions of the gridshell and displayed the cushioning aesthetics. Again, there is a presence of dominant lines brought about by the impression of the upper layer of grid-laths which was observed in test shells 1, 2, 3 and 4. The openings brought light into the spaces within.

The limitation lies in scale. A true comparison between a scaled model and the actual construction as some steps and processes that are accurately replicated in terms of the actual construction remains a challenge. Especially for scaled models that investigate accuracy of process, form and thicknesses using actual materials to construct the mock-up may not always translate well (Addis, 2013). For example, the way the gridshell attaches to the abutments and also the manoeuvring of formwork at a large scale are not necessarily true to life-scale constructions.

Fig 10.30. The interior spaces are illuminated.

Fig 10.31 Concrete shell interior bore the impression of the gridshell formwork.

10.4 Dimensional Analysis

When the gridshell was removed, the imprints of the gridshell on the underside of the concrete shell is clearly visible. Again, the uppermost layer of the gridshell produced dominant lines (Fig 10.31). The cushions and indentations appear to have a smaller variation at this scale as well. When measured using a pair of callipers, the gridshell thickness ranged between 10mm and 15mm. This equates to measurements between 200mm and 300mm at life-scale since the model is scaled at 1:20. As a scaled model, the scale of the model described a completed building whilst previous mock ups had a bigger grid size to span ratio compared to the grid-size to span ratio for Downland gridshell at 1: 12.5 = 8% (narrowest).

The variation between grid-size and shell span is smallest amongst all the tests conducted.

1. test 1 (200/1300 = 15%),
2. test 2 (200/1350 = 14.8%),
3. test 3 (300/2950= 10.2%) and
4. test 4 (200/2220 = 9%).

10.5 Aesthetics

Fig 10.32 a top A view of the resultant concrete shell cast over the Weald and Downland gridshell as formwork. b) the actual building as it stands. Both buildings share the same shell form but are expressed differently in terms of material and tectonics: one as concrete and the other in timber, one monolithic and heavy, whilst the other light-weight and flexible. Both allow light to fill the interior space.

Firstly, the main feature of the shell is the gridshell pattern is clearly expressed on the underside surface of the shell. As with previous building tests, areas between grid-laths formed cushions whilst indentation imprints located the pattern of the gridshell formwork, clearly demonstrating a strong stereogeneous solution. As well, dominant lines by deepest indentations apply here as a result of the top most grid lath that supported the fabric and eventually concrete. However, due to the rigidity of plaster of Paris bandages, used in this scaled down model, wrinkles and folds were formed as a result of how the fabric clumped together and how they were handled after being hydrated. These anomalies associated with scale of the model and would not appear at the construction at life-scale as this process is not used.

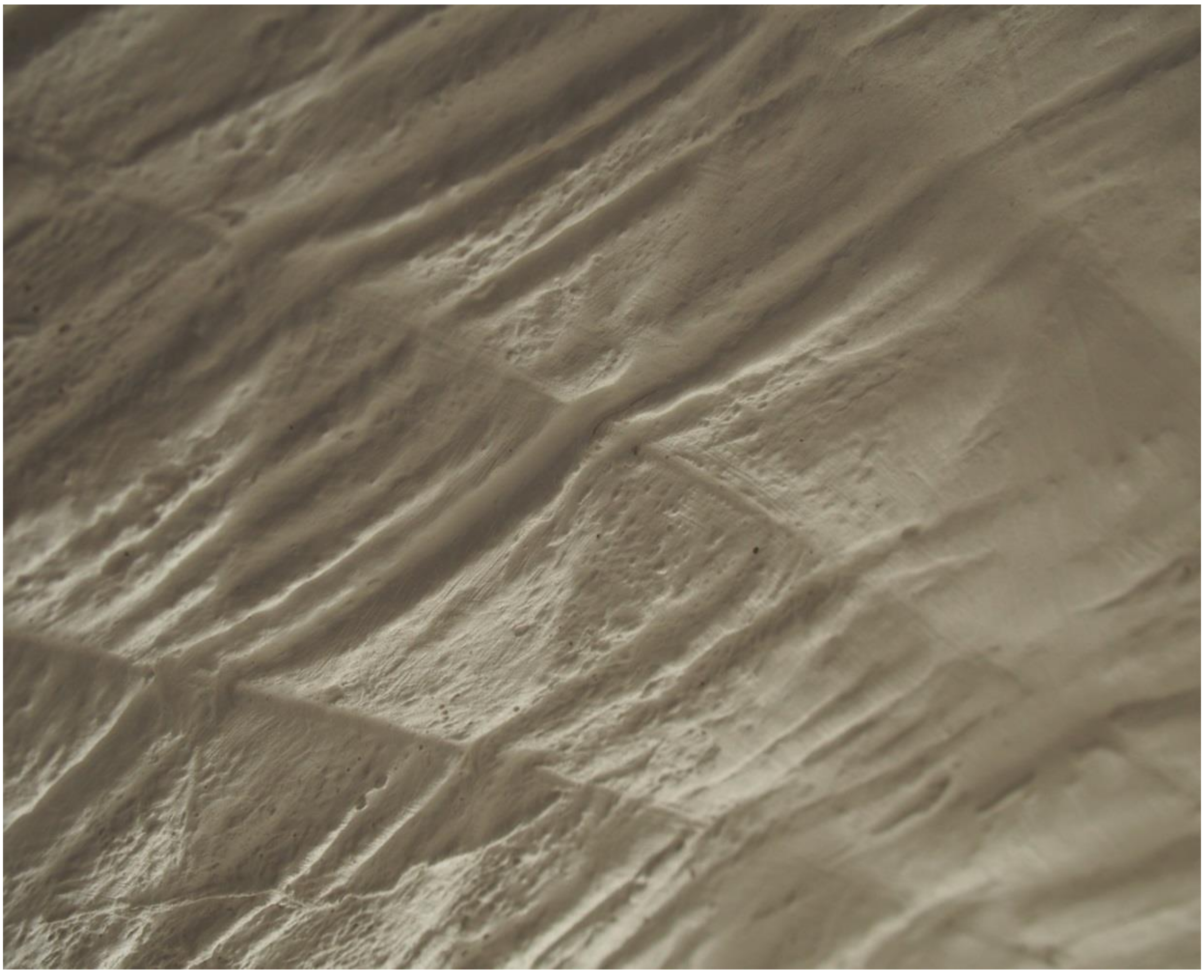


Fig 10.33 textured close up of fabric showing strong stereogeneous idea Manelius, 2012)

10.5.1 Perception of Thinness

Indentations and cushioning appear to have lower variations compared to previous test builds. They appear slight and shallower compared to previous tests. Measuring between 10mm at indents and 15mm at thickest cushions in the model, this represents a thickness range between 200 and 300mm in the actual concrete shell. A thickening of the cushions at the abutments was not noticed. A quick ratio thickness variation (of the entire shell) to grid size comparison is found:

	thickness variation/mm	gridsize/ mm	ratio (%)
Test 1	62.9 - 9.3 = 53.6	200	26.8
Test 2	67 - 11 = 56	200	28
Test 3	40 - 20 = 20	300	6.7
Test 4	63 - 17 = 46	200	23
Simulation (Downland Model)	300 - 200 = 100	1000	10

Table 10.1 **THICKNESS VARIATION TO GRID SIZE RATIOS**

Test Shell 3 (Chapter 8) appeared more evenly thin as a result of using metal sheets. The small variations of thickest and thinnest measurements help to give the impression that the shell was thinner. This qualitative perception of shells thickness offers valuable aspect of assessing concrete shells constructed using this method. From the result of shell thickness to grid size ratios, it suggests that the visual impressions of the inside shell surfaces may bear no relationship to the structural thinness of the shell when seen from within the shell. The first visual impression of the shell surface comes from being inside the structure. It suggests that by reducing the variation of shell thickness, an illusion of thinness seen within the shell can be achieved.

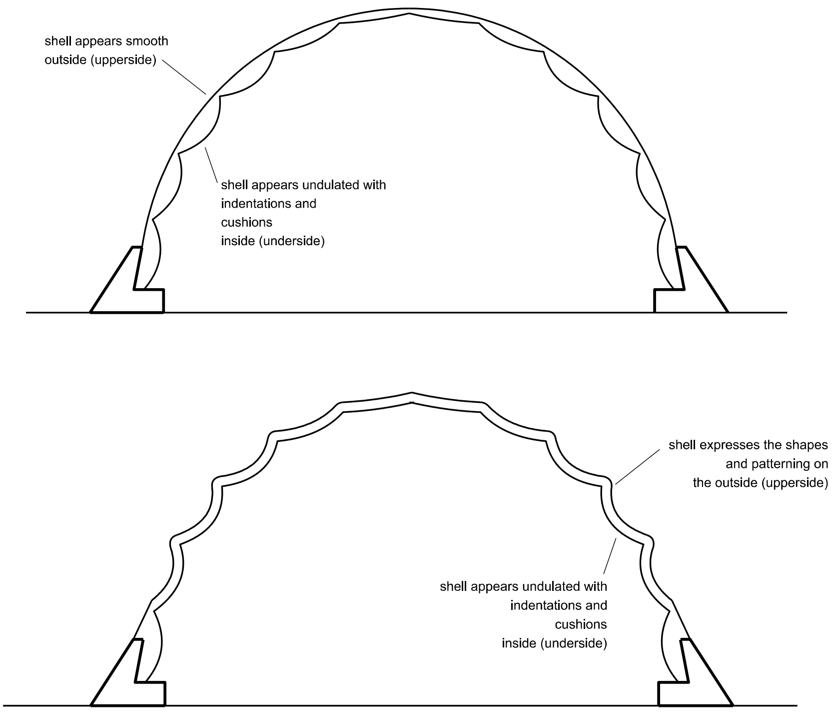


Fig10.34 Seen from the inside, there is no difference between shell 1 and shell 2 - they both express the same patterning on the inside of the shell although structurally, this differs. The visual impressions/ understanding of the shell structure may not relate to the structural functions directly.

This perception of structural thinness by reducing thickness variations may be attributed to the two stage casting process: firstly, the thin layer of plaster of Paris bandages which was allowed to cure, then an additional layer of concrete applied on top. The lower layer therefore determined the visual expression of the construction whilst topping concrete performs a structural function to reinforce the shell with impact to the appearance of the shell on the upper side i.e. outside.

This emphasises the importance of this first stage of concreting to achieve visual thinness. This aesthetic may be achieved by using a tight fabric to suspend a thin layer of concrete. Being able to create a thin efficient surface (less cushioning) agrees with the structural aim of concrete shells - to create structures with material efficiency to span large distances through shape effectiveness and not mass.

Another reason for this perception of shallow cushioning may be due to shell heights i.e. distance of the cushions away from eye level. By comparison, simulation modelling of the Weald and Downland gridshell attempted to convey the tallest space by far. A direct comparison of their height to span ratios is presented in the table below. The height to span ratio of the Weald and Downland Gridshell recorded 9.5m/ 16 m ie 59% compared to earlier tests.

	rise/mm	span/ mm	ratio (%)
Test 1	492	1300	38
Test 2	620	1350	46
Test 3	1152	2950	39
Test 4	930	2200	42
Simulation (Downland Model)	9,500 (tallest points on section)	16,000 (widest point on plan)	59

Table 10.2 **SHELL RISE TO SPAN RATIO**

10.5.2 Tectonic, illumination and Atmosphere

The cushioning of the under surfaces of the concrete shell suggests a purpose to vary atmospheres and illuminance. From the model, patterning appeared most dramatic when light shines onto the shell interior at an oblique angle (e.g. low light in mornings, evenings). This light dramatically highlights and accentuates details and textures of the undulating surface which is a strong tectonic feature. These observations are illustrated in fig. 10.35 a and b as comparison between the way these shells appear under different natural lighting conditions. The shape of the shell and the extensive surface also presents opportunities to increase reflectance by acting as a reflectance surface. Additionally, the increased surface area may impact the space within thermally. Therefore, this aesthetically textured surface therefore presents an opportunity to regulate spatial quality and temper the internal environment enclosed by the shell.

Fig 10.35 Different lighting effects of internal shell surface.

Fig 10.36 The openings of the shells allows natural daylight to penetrate and illuminate the spaces.

Fig 10.37 The extensive surfaces of the shell could reflect light and illuminate the internal surfaces.

10.6 Structural Analysis

With constructions of mock-ups and models addressing feasibility and constructional practicalities of this technology, the performance and viability of a surface structure such as a concrete shell constructed this way will be examined. Although the process of construction has been interrogated and discussed, constructional and aesthetic issues, some structural questions could not be answered from building model simulation alone. As it is practically not possible to construct a life-size building to study the structural behaviour due to limitations in resources i.e. time, space, cost and material, to address these questions, structural analysis of the system is carried out with the engineering expertise of Mr Jaffel Versi of Arups, Sheffield.

Issues raised earlier about structural aspects of the shell presented specific questions such as:

- How strong is the resultant concrete shell?
- How does this affect the construction process of the shell?
- How thin can this concrete shell be?
- How does this thickness of this concrete shell compare with historical examples of concrete shells. Does this method allow concrete shells to be built better?

10.6.1 Structural performance of concrete shell.

To perform a finite element analysis of the shell, a digital 3D model of the form-found shell was provided by Chris Williams at Bath University. Prof Williams worked on the form-finding of many shell projects including the roof at the Great Court in the British Museum (2000), the Weald and Downland Gridshell (2002) and the Savill Garden gridshell (2005).

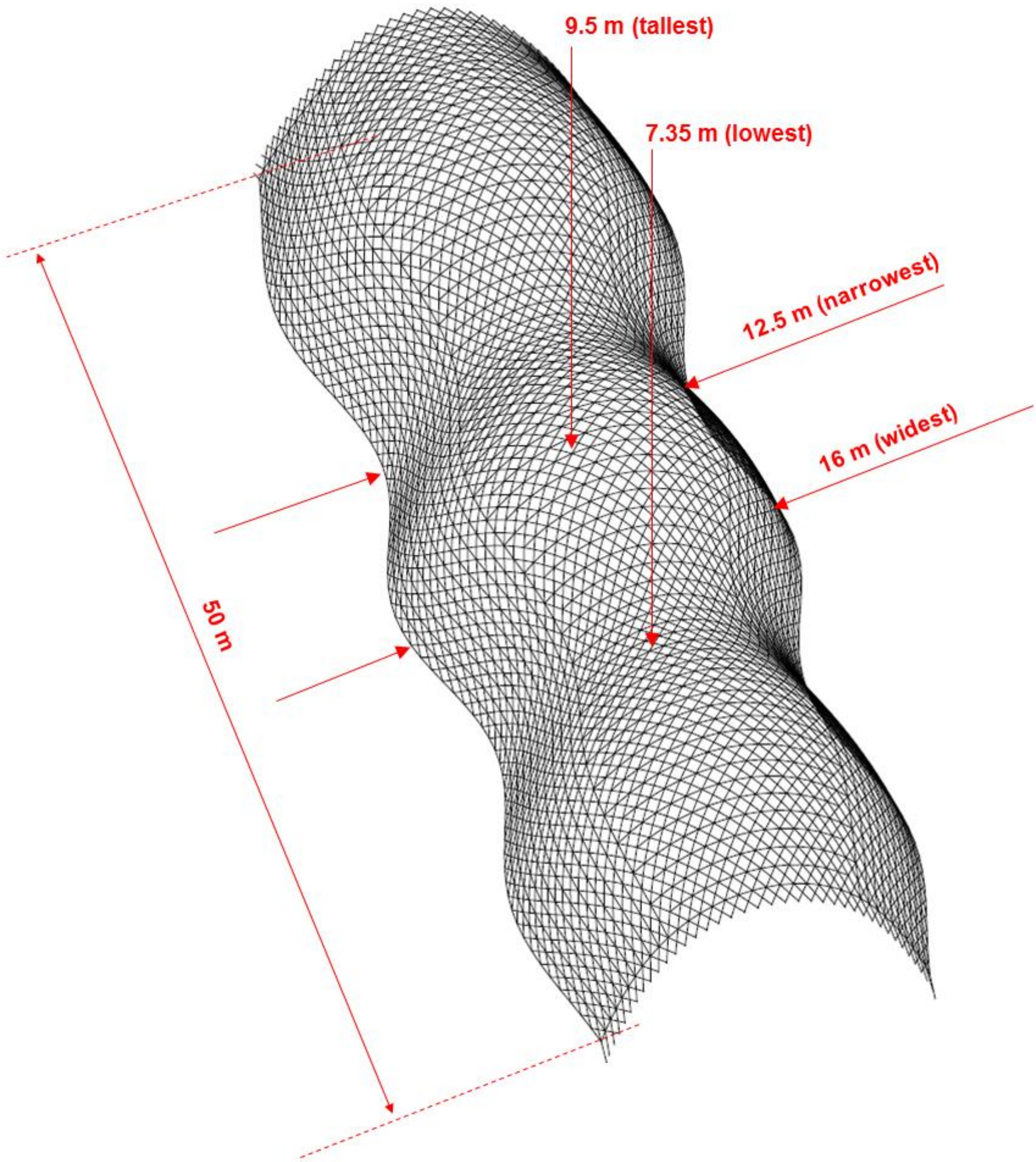


Fig 10.38 Digital 3D model of the formfound model for Weald and Downland Gridshell (courtesy Chris Williams)

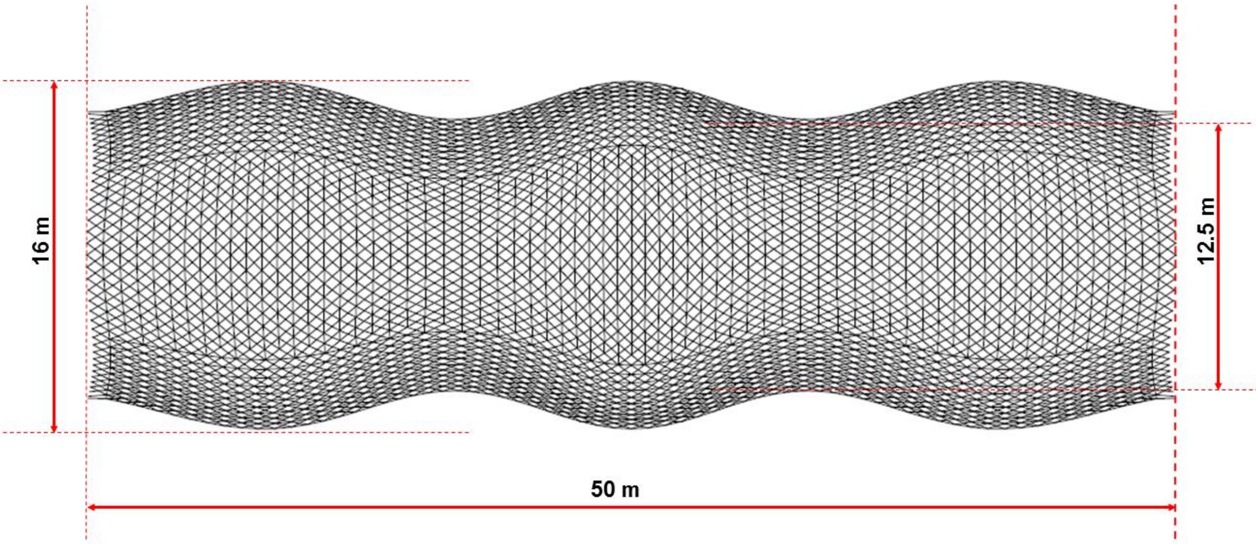


Fig 10.39 Digital 3D model of the formfound model for Weald and Downland Gridshell. Dimensioned on plan (courtesy Chris Williams)

10.6.2 Structural performance by FE Analysis

The form-found model of the Weald and Downland gridshell was used to check for structural performance of the form.

To carry out the analysis, some parameters are set.
For the purpose of this exercise, it is assumed that 100mm tubes were used to make the gridshell in a single lattice.

The following steps were taken to produce the analysis:

1. Analyse the gridshell, based on 100mm diameter grp tubes supporting a mesh, onto which was sprayed 20mm of concrete.

2. The resulted deflected shape of the tubes (with 20mm of concrete weight only on it) was then converted into another analysis model, which was meshed to form a shell surface of a 20mm concrete that sits on top of the deflected grp gridshell formwork.

3. This 20mm shell then had the weight of a further 80mm of wet concrete applied.

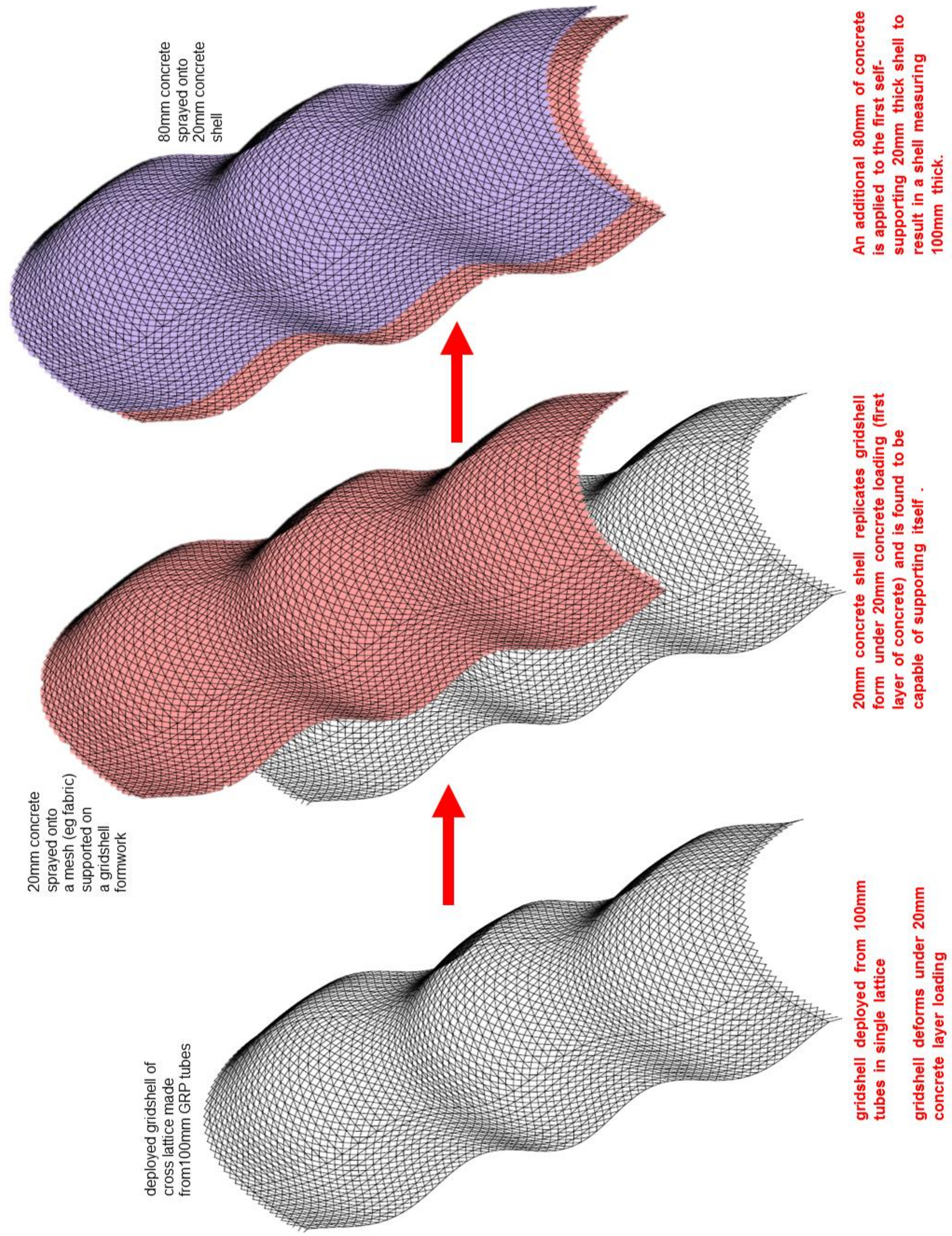


Fig 10.40 Schematic diagram explains the rationale of FEA. (courtesy Chris Williams and ARUPs)

Carried out on Oasys FE software, the following finite element analysis describes the behaviour of the 20mm RC shell cast over a deformed GRP gridshell formwork.

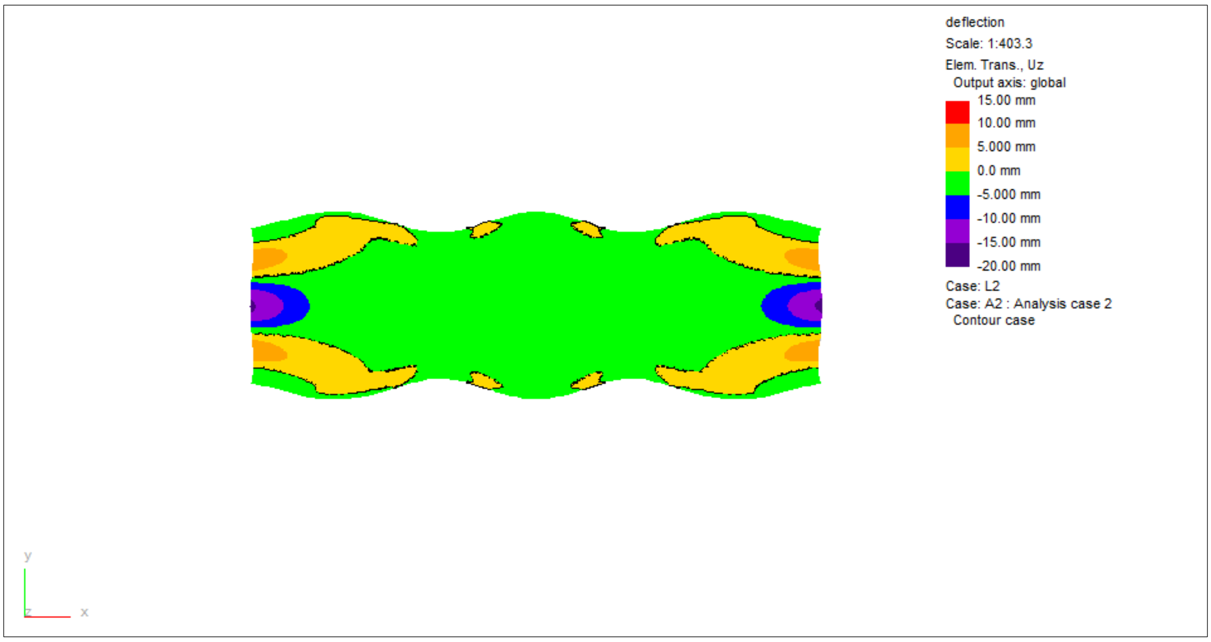


Fig 10.41: 2017-06-02 Gridshell RC deformed shape 20mm_deflection (0) (courtesy ARUP)

Deflection is very low for the 20mm deformed RC shell due to a previously form-found shape with strong structural efficiency. A predominance of green area indicates deflection between 0mm and -5mm within most of the shell. The highest deflection regions are found at the apex of opening edges with a deflection to -20mm.

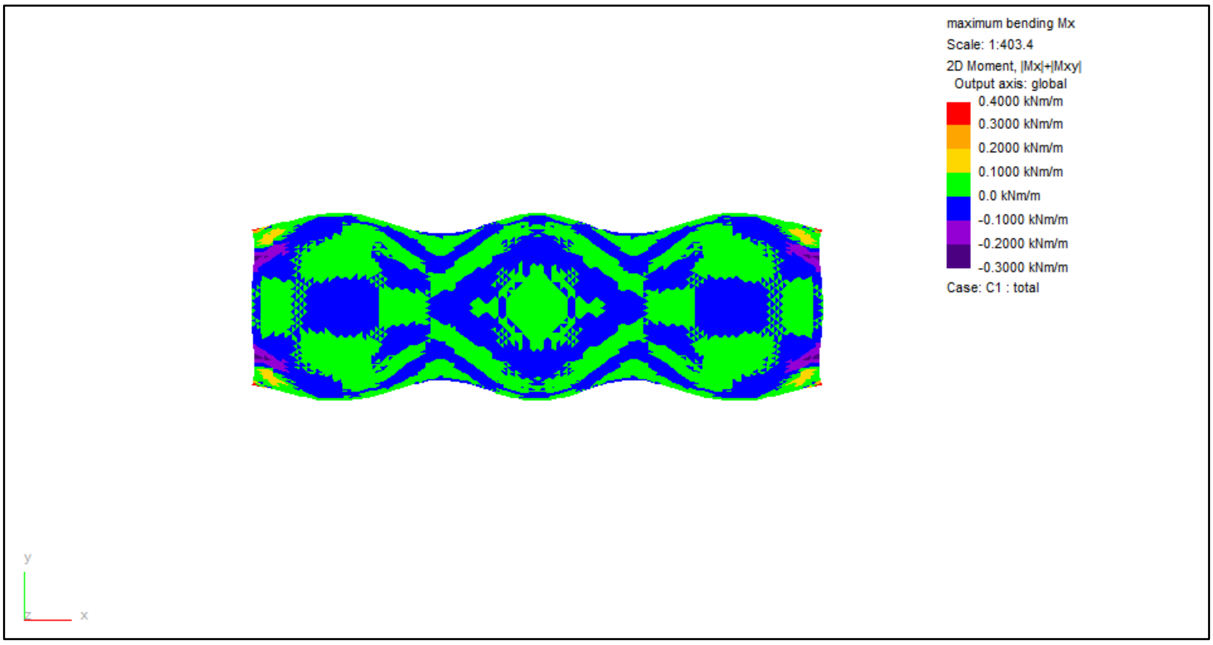


Fig 10.42: 2017-06-02 Gridshell RC deformed shape 20mm_maximum bending Mx(0).png (courtesy ARUP)

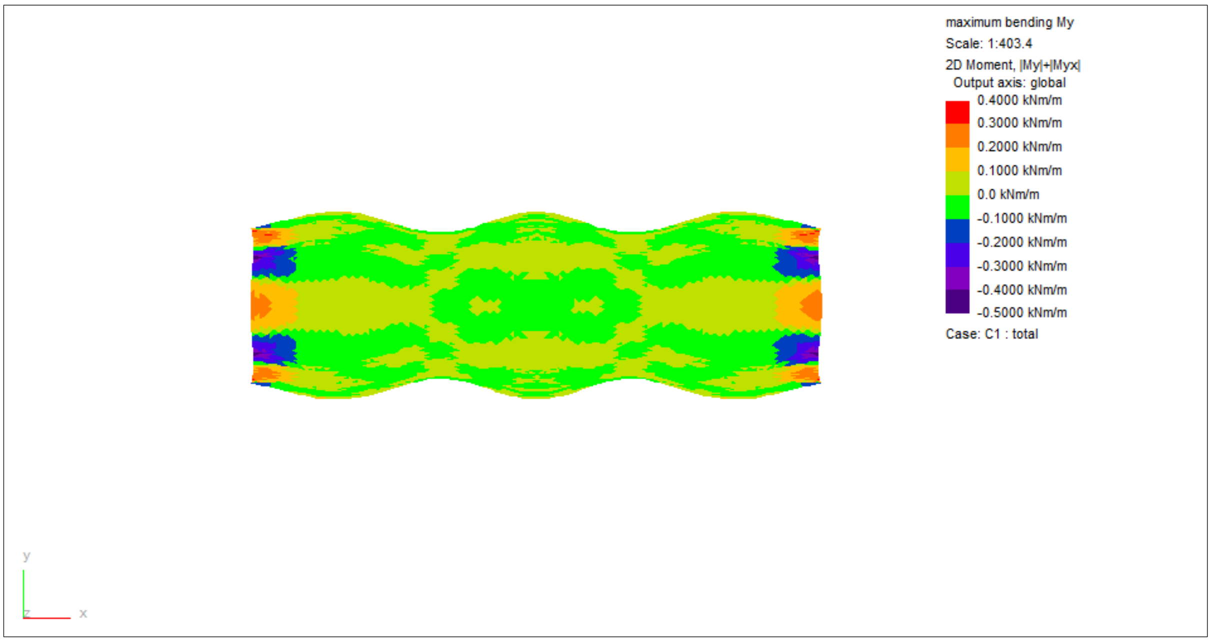


Fig 10.43: 2017-06-02 Gridshell RC deformed shape 20mm_maximum bending My(0).png (courtesy ARUP)

At maximum bending on the x and y axes, bending moments for the shell in X and Y directions (fig. 10.42 and fig. 10.43 above) are low, yielding results in the magnitude between +0.1kNm/m and -0.1kNm/m. The FE diagrams indicate free edges as being most vulnerable (although to small magnitudes).

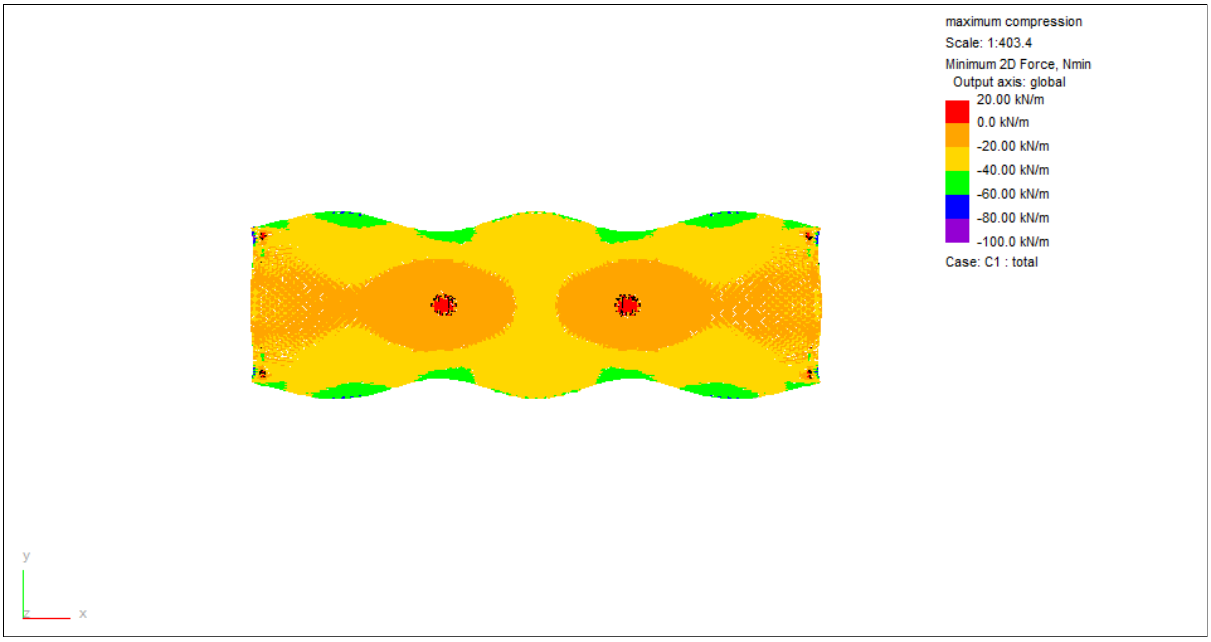


Fig 10.44: 2017-06-02 Gridshell RC deformed shape 20mm_maximum compression(0).png (courtesy ARUP)

Referring to fig 10.44, at maximum compression modes, bending moments act mainly between 0kN/m and -40kN/m (orange and yellow). Small areas in the valleys (red) and at points along the free edge (red) indicate bending moments of between 0kN/m and 20kN/m.

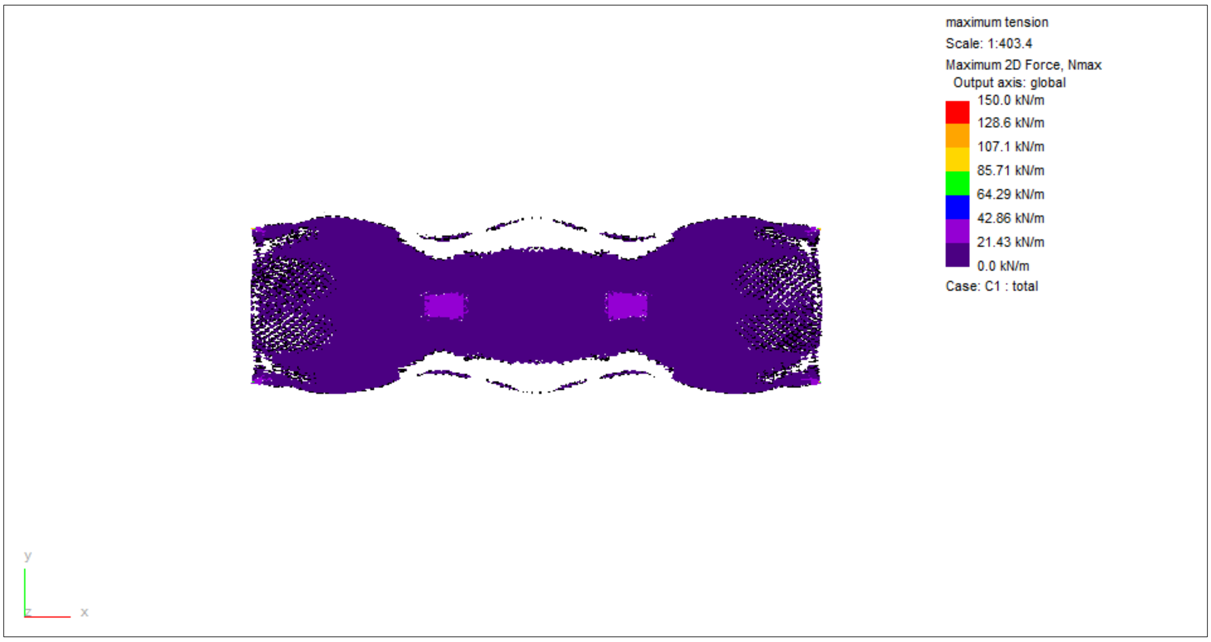


Fig 10.45: 2017-06-02 Gridshell RC deformed shape 20mm_maximum tension(0).png (courtesy ARUP)

The predominance of the low maximum tension experienced (represented by purples) translates into a working requirement of 96mm2 of reinforcement/ metre required. This is equivalent to 5mm diameter bars at 200mm centres. This amount of reinforcement would need to be applied to this shell layer four safety.

Carried out on Oasys FE software, the following FE analysis describe the behaviour of the 100mm (ie 20 + 80mm) RC shell cast over a deformed GRP gridshell formwork supporting an imposed load of 0.6kN/m2 and applied as pattern load.

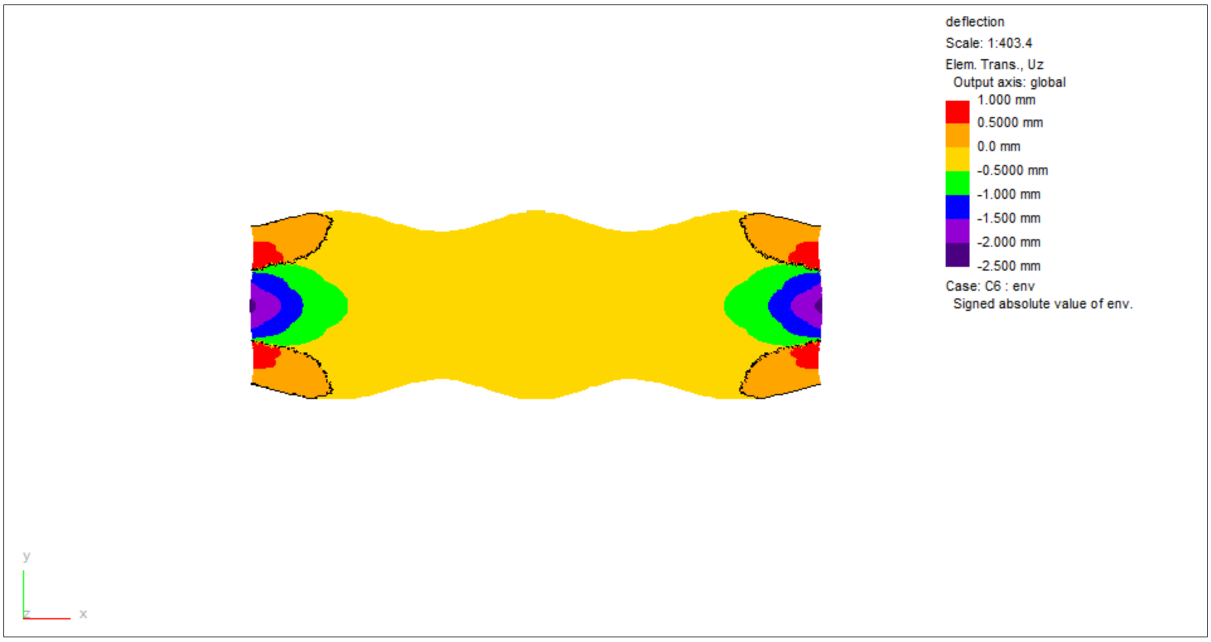


Fig 10.46: 2017-06-02 Gridshell RC deformed shape 100mm_deflection(0).png (courtesy ARUP)

The predominance of yellow regions indicate low deflection at this loading mode. Free edges experience larger deflection between 1mm to -2.5mm, which is very small. Compared to the 20mm thick RC shell (with deflection value between (+10mm and -20mm), the additional 80mm thickening of shell has strengthened the shell to deflect less.

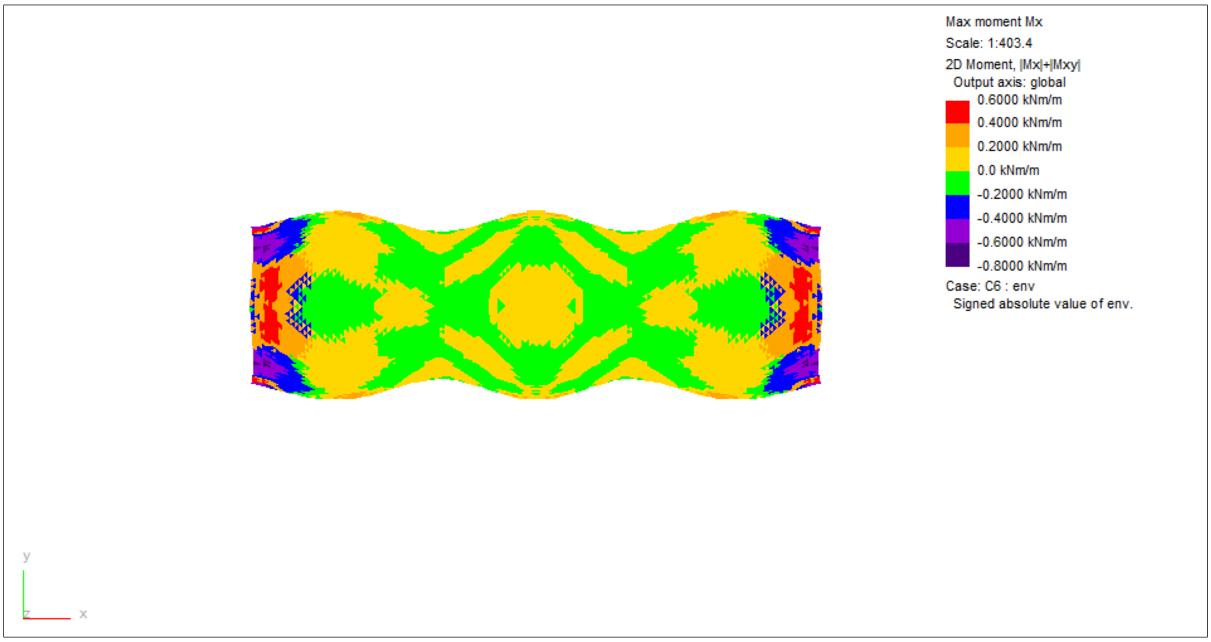


Fig 10.47: 2017-06-02 Gridshell RC deformed shape 100mm_ Max moment Mx(0).png (courtesy ARUP)

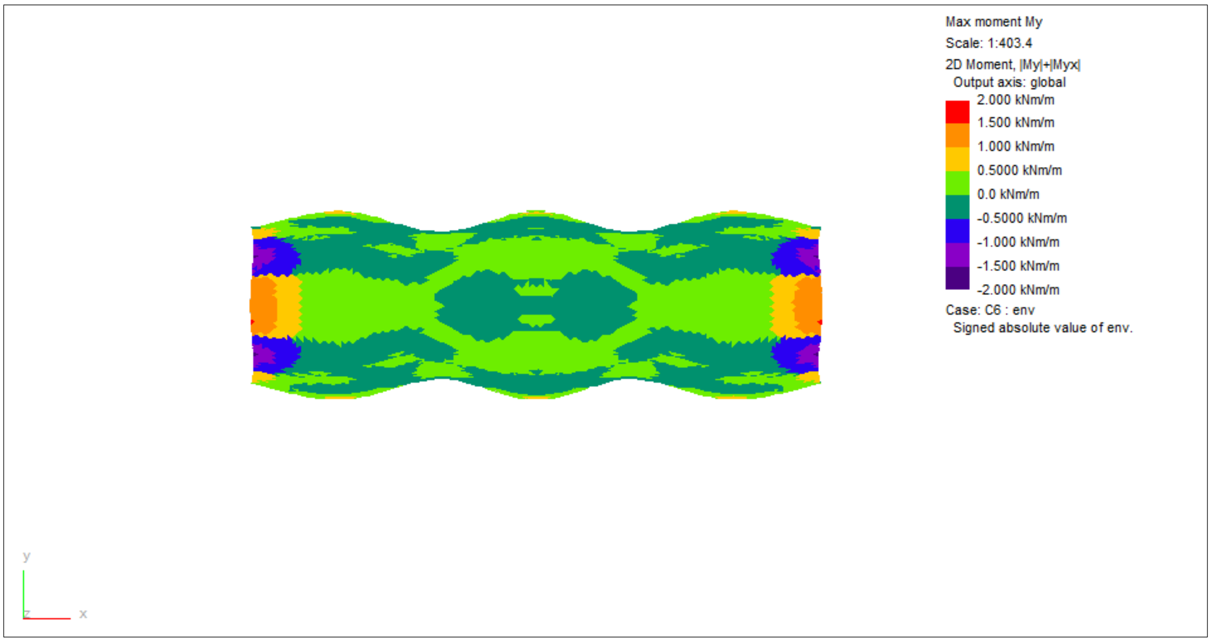


Fig 10.48: 2017-06-02 Gridshell RC deformed shape 100mm_Max moment My(0).png (courtesy ARUP)

At maximum bending on the x and y axes, bending moments for the shell in X and Y directions (fig. 10.47 and fig. 10.48 above) are low, yielding results in the magnitude between +0.5kNm/m and -0.5kNm/m. Again, the FE diagrams indicate free edges as being most vulnerable which may be strengthened by thickening concrete at these regions or incorporating more reinforcement mesh at the open ends.

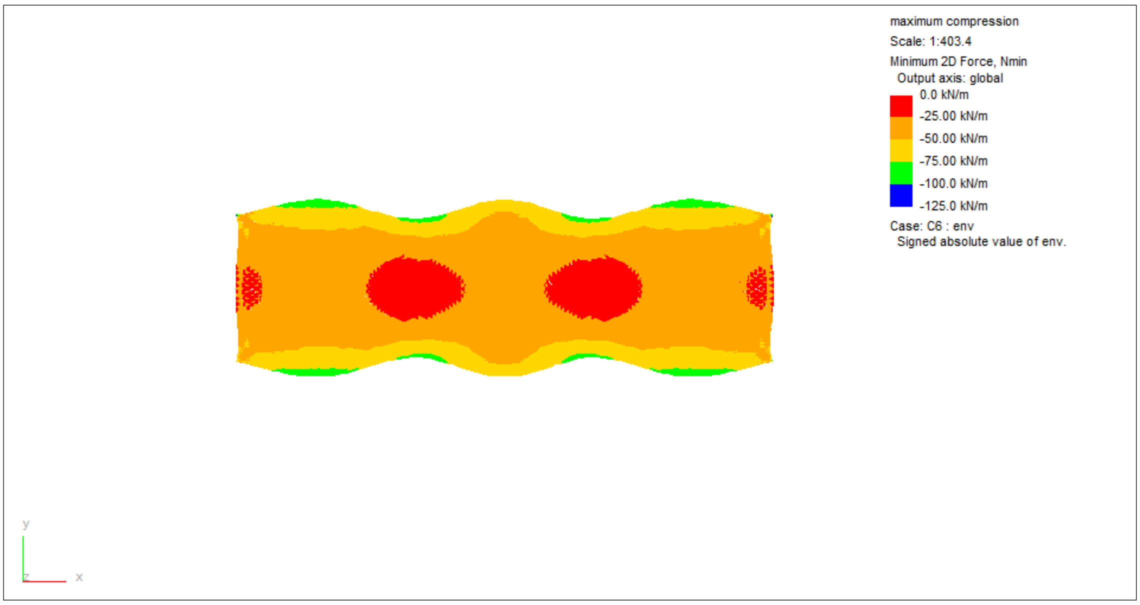


Fig 10.49: 2017-06-02 Gridshell RC deformed shape 100mm_maximum compression(0).png (courtesy ARUP)

Referring to fig. 10.49, at maximum compression modes, bending moments act mainly between -25kN/m and -75kN/m (orange, yellow and red). Areas in the valleys (red) and at points along the free edge (red) indicate bending moments of between 0kN/m and -25kN/m.

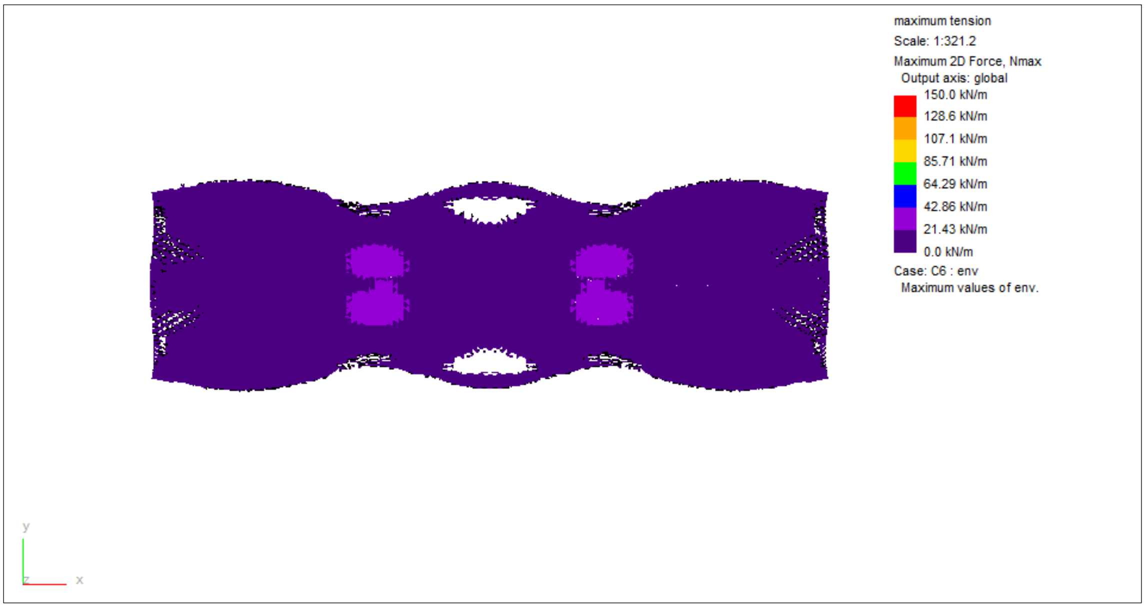


Fig 10.50: 2017-06-02 Gridshell RC deformed shape 100mm_maximum tension(0).png (courtesy ARUP)

Results of this composite shell in tension displayed similar patterns to the 20mm concrete shell with ranges similar to that displayed earlier. As such, it is deemed that no additional reinforcement over and above the 96 mm2/ m which is already provided within the 20mm layer is required.

10.6.3 Results

- Verified by ARUP, through finite element analysis, it was found that when gridshell was constructed by deploying a gridmat made from a lattice composed of 100mm diameter GFRP tubes, a concrete shell can be built.
- The analysis has found that a resultant concrete shell of 100mm thickness is possible.
- The analysis suggests that it is better to cast concrete shells in layers. In this simulation, the shell was cast in 2 layers: the casting of the first concrete layer can create a strong secondary shell formwork. It was found to me more material efficient (for the same strength) than in a single casting. Initial analysis by ARUP to cast at one single layer would require a very deep gridshell to be built.
- For this simulation in question, an initial layer of 20mm concrete was applied onto a mesh supported by the braced and rigidified GFRP tube gridshell in the efficient form of Weald and Downland Gridshell.
- At this point, the gridshell underneath could be decentred. However, deemed brittle, it should be left intact.
- From the analysis, a working requirement of 96mm2 of reinforcement/ metre is needed. (equivalent to a simple metal mesh of 5mm diameter bars set at 200mm centres or meshes of glass reinforced plastic or carbon fibre to achieve similar structural specifications). This amount of reinforcement would need to be applied to this shell layer for structural safety.
- A further layer of 80mm un-reinforced concrete could be applied onto the earlier 20mm hardened reinforced shell.
- The resultant 100mm shell would have low deflections.
- Finite element analysis has confirmed that reinforcement meshes are not required in this layer of concrete.
- The gridshell underneath could then be de-centred and be re-used as new formwork.

10.7 Limitations

This exercise did not take into account heavy windows or openings which may affect imposed loads onto the GFRP gridshell, Their impact would be significant if they are very heavy and or if there are many and their distribution (whether concentrated i.e. unbalanced or evenly dispersed). Openings may cause uneven loading which as shown in all test shell constructions will cause the shell to deform with geometrical results of the shell.
Secondly, this analysis assumed a curved shell without cushioning as a result of the casting process which may add additional loads.

The analysis did not take into account the application of insulation which is imagined to be sprayed, expanded and applied onto the final completed shell.

10.8 Discussion

10.8.1 Openings/ Light and Air

Especially if they are specified as gridded glass blocks similar to the ones used at Prada Aoyama in Tokyo by Herzog and Meuron, 2003 (fig. 10.26), their use impacts on the loads on the finished concrete shell. Felix Candela used glass blocks arranged on grid to bring light into the factory space in the hypar roof at High Life textile factory in Mexico City (1955). However, the glass blocks have now been painted over.

Fig 10.51: Interior of High Life Textile Factory (now Cavalier Industries Factory), Mexico City (1955)

The use of temporary scaffolding towers supporting each window or *resist impacto* could be installed as temporary guides to maintain these key points in the x, y and z axes as was conducted in Test Shell 3 to solve the problem of deflections during the concrete casting. The need for openings/ positioning of glass windows could be integrated in the construction process to provide *resist inpacto* supports and formwork stabilisation during the casting process to achieve the desired designed geometry.

10.8.2 Geometry accuracy and gridshell erection

PERI-UP scaffolding towers, used for the Weald and Downland gridshell may be employed again to raise the initial flat gridmat from the ground as well as supporting a glass block window or *resist impacto*. Instead of lowering gridmats from raised level, it is envisaged the GFRP gridmat would be raised from the ground due to the elastic nature of GFRP using a crane.

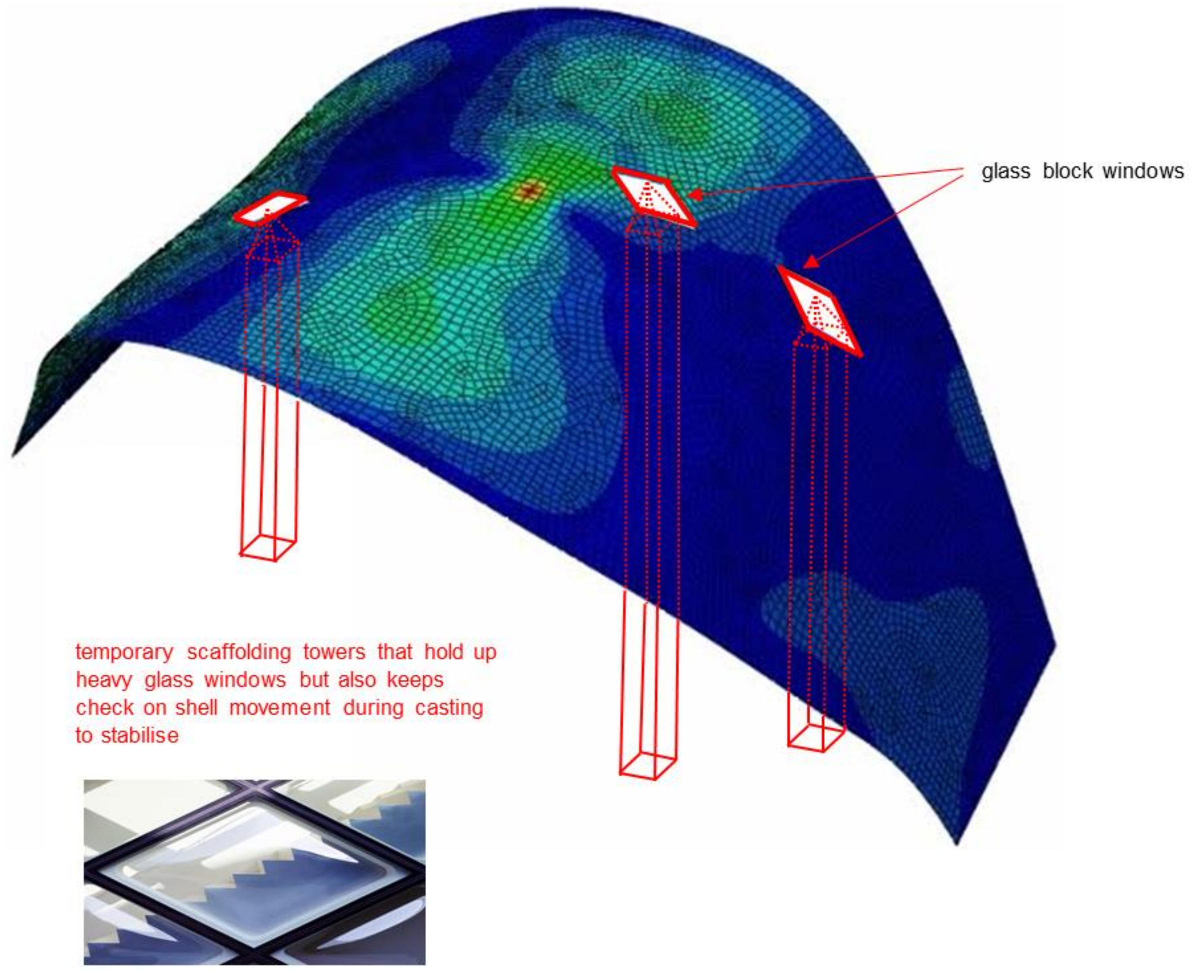


Fig 10.52: The uses of temporary scaffold towers supports glass block windows or *resist impactos* and act as stabilizers to prevent the flexible gridshell formwork from deflecting excessively during casting phase.

10.8.3 Concrete Adhesion

When concrete is applied in two separate layers, concrete adhesion may pose a problem. As reinforcement meshes are used in the lower 20mm layer, mesh extensions from the re-bar meshes may be specified to allow connection between the two layer of concrete to become seamless and act structurally as a single entity.

10.8.4 De-centring Stages

As the first concrete layer cures to structural strength, the formwork could be removed. However, this 20mm shell although structurally stable, may be brittle and be susceptible to damage/ cracks if it was decentred too soon. Results of the finite element analysis suggest the suitable conditions to decentre only after the top layer was applied and cured.

10.8.5 Shell thickness

To monitor shell thickness of 20mm, stubs such as that used in test 3 could be installed at gridshell intersections to ensure that concrete layer is even.

Connection to abutments and foundation details will need to be designed carefully with structural engineering help.

10.9 Conclusion

This experimental construction and finite element analysis has been useful in answering and discussing the questions set out at the beginning of the chapter. This has proved that a building of similar scale of the Weald and Downland gridshell by using deployable gridshell is possible.

10.9.1 Construction

By constructing one half of a 1:20 scale building of concrete shell by using the Downland gridshell as formwork, to a limited extent, some issues of scaling was experienced. However, the technology worked well as a replica of the Weald and Downland gridshell. With the intention to repeat the use of formwork for reuse, how the shells connect together need to be taken into consideration. The joints offer light penetration as have been used in many of Felix Candela's shells. The building may be composed of a series of these individual concrete shells with the gaps between expressed to allow as lighting gaps.

Another way of allowing light to enter the building is by creating openings on the surface of the shell as was demonstrated. One method is to cast in situ glazed blocks (which are left within the concrete surface) or *resist impactos* which form openings in the concrete shell (and removed after the shell is cured.

In life-scale construction, abutment details and foundation details need to be designed with the structural engineer.

10.9.2 Aesthetics

Pattern of gridshell formwork is highly visible in the underside of the concrete shells with the appearance of dominant upper level gridlaths. Resultant shell strongly exhibits ideas of stereogeneity.

This new shell model appears thinnest out of all the tests. It also appeared less undulating. With casting the shell in 2 stages, it was possible to create a thin shell with low thickness variation helping to give the visual impression of thinness. Secondly, the scale and rise of the shell impacts on perception of shell thinness.

With the resultant concrete shell offering a large curved surface area of reflectance, various architectural atmospheres can be created. Light entering at an oblique angle is useful in picking up the cushioning textures to create a dramatic appearance. Openings set within the model enabled light and air to enter the space of the deep set plan.

10.9.3 Structural analysis:

FEA conducted by ARUP recommends the casting in two stages with the first casting creating a thin metal mesh reinforced concrete shell structure onto which second cast concrete is applied. This allows cushions to remain shallow, hence creates a more efficient concrete shell with less deadweight.

The construction/ erection process for this project is envisaged to be pushed upwards from the ground using the PERI-UP system. Individual towers support glass block windows or *resist impactors* together with the gridmat. Their application serve three purposes: firstly, this can act as a monitoring device to check for specific point heights on the gridshell. Secondly, they support glass block windows or *resist impactos* which are heavy. Thirdly, they can be used to raise the gridshell. Finite element analysis confirms the possibility of a 100mm concrete shell being possible using this technology.

Therefore, the structural analysis and model construction simulation has verified the possibility of constructing concrete shells using gridshells as formwork.

Detail, Downland Shell, 2017 (Gabriel Tang)

PART 4 ASSIMILATION AND CONCLUSION

Chapter 11 CONCLUSION

Chapter 11: Conclusion

11.1 Summary of the study:

This PhD work proposed the use of deployable glass reinforced fibre glass gridshells as temporary, reusable and reconfigurable framework to support fabric onto which concrete shells are cast.

Examining the factors that led to the fall of concrete shells in Chapter 3.4 revealed the close relationship between concrete shells and their formwork. With particular attention paid to formwork, a survey of methods available to craft concrete shells was discussed and assessed in Chapter 3 and 4. Through these, the close relationship between formwork and the concrete shells that resulted was scrutinized. This new shell construction method is synergized by three architectural technologies: concrete shells, fabric formwork and deployable gridshells.

Flash research modes of exploration and experimental workshops (Chapters 2 and 5.6) investigated the construction of deployable gridshells to inspire the hypothesis aimed at addressing the shortcomings associated with concrete shell construction methods.

The idea is tested by the construction of four concrete shells using this system (Chapters 7, 8 and 9). Test shells 1 and 2 in Chapter 7 verified the feasibility of the hypothesis. In Chapter 8, Test shell 3 emphasized the importance of a suitable gridshell material. Each test shell was comprehensively measured and analysed with a focus on construction, aesthetics and structural performance. The behaviour of the gridshell formwork was examined in terms of movements during construction whilst the resultant concrete shells underwent geometric scrutiny and structural analysis. Failure tests were carried out to each test shell to assess the strength of each resultant concrete shell.

The final test shell 4 (Chapter 9) demonstrated developments, and elaborated the possibilities of using this system to create concrete shells with openings, simplified abutment system and with an expressive flared free edge that demonstrated how this novel system can be used to create thin concrete shells.

A representative simulation of the Downland gridshell construction was carried out at 1:20 scale to replicate the construction of a shell using this principle and presented in Chapter 10.

All tests and construction strengthened the feasibility of this type of construction method. Test shells 1 and 2 (Chapter 7) evidenced the reusability and reconfigurability of such a system. Test Shell 3 (Chapter 8) showed that a shell with even thickness is possible to achieve. Test Shell 4 (Chapter 9) demonstrated the creation of the free shell edge, the enhancement of strong double curvatures by manipulating the deployable gridshell gridmat. The simulation of a concrete shell using the Weald and Downland as formwork (in Chapter 10) showed that a shell of a defined gridshell geometry can be made by casting concrete over a deployed and form-found gridshell.

11.2 Design

11.2.1 Form-finding/ Form-making

The experimental work on hanging chains and actively bent paper models have shown that the deployable gridshell can be used as an intuitive form-finding tool for designing shells. Earlier experimental work have also shown that both proper and improper shells (as described by Candela in Garlock and Billington, 2008) can be constructed by using gridshells as form-finding/ form-making tools as well as actual formwork for shell casting. This is evidenced in Chapter 6.3.

Compared to hanging membrane method used by Heinz Isler, points on the hanging gridnet can be easily translated from each grid intersection into an inverted gridshell formwork used in conjunction with digital tools such as 3D CAD and finite analysis software to create a compressive shell. Additionally, a physical deployable gridshell model can also be used to generate “improper” shell forms (i.e. shells with bending moments). As a design tool, scaled gridshell models offers the designer (engineer and/or architect) structural intuition and the opportunity to use deployable gridshells as a versatile means to tailor shell designs to meet architectural needs. This method of form-finding/ form-making integrates construction thinking as well, something not offered by existing means of building concrete shells. Compared to fabricating bespoke glulam beams to create formwork, this system is visual, spatial and intuitive as it readjusts according to forces applied for the design of shells universally (i.e. for both proper and improper shells). A material which readily moulds to form, concrete (liquid at first, and setting to solid afterwards) is suitable in covering a doubly curved gridshell surface to then solidify and eventually becoming a loadbearing structure.

11.2.2 Details, Construction Details

From the design and construction processes of test shells 1, 2, 3 and 4, edge detailing were exercised by the use of the same tubular materials which formed the gridshell to inform an architectural language. Concrete forming is integral to the overall aesthetic of the final concrete shell. The sharp concrete edge details were achieved by the use of tubes (also used to create the gridshell) to sharply defined edges in test shells 1 and 2 with a tectonic consistency.

11.2.3 Thickness Control

In test shell 3, the control of thickness was monitored by installing needle/ markers on the upper surface of the gridshell formwork to ensure an even concrete thickness. The markers allowed an even spread of concrete.

11.2.4 Abutments At the beginning, abutments were separately pre-cast and attached onto the baseboards. They were progressively simplified, eliminating the need to cast separate abutments. The shells proved that doubly-curved shells could be constructed with deployable gridshells, even with straight abutments.

11.2.5 Shell Thinness

Edges are important expressions of shell thinness and require careful design. Test shells 1, 2, 3 and 4 suggested different ways of forming the edges to accentuate this quality.

This method of construction further exemplifies fabric formwork use, adding to their use as surface and filled moulds (Veenendaal and Block, 2011, West, 2016). This helps to support, encourage and further validate fabric formwork use in architectural applications as an emergent technology.

11.2.6 Openings and top lights

The Weald and Downland gridshell simulation allowed two bands of longitudinal clerestories similar to the polycarbonate panels of the original Weald and Downland gridshell sending top light into the space below. This concrete casting simulation revised this architectural vision and interpreted it using this new method to recreate the same lighting concept. Test Shell 4 (Chapter 9) and the Downland simulation (Chapter 10) discretized grid units into triangular framed units meaning that smaller openings, placed in clusters can realise the lighting scheme, yet staying true to this technology. It demonstrates a technological approach which is sympathetic to means (construction) and material (concrete, GFRP and fabric).

11.2.7 Gridshell Material: GFRP

The experimental search of a suitable gridshell material for use in this architectural application identified GFRP (glass-fibre reinforced plastic) as a suitable material for making gridshells in this application. Test Shell 4 and the final 1: 20 Downland construction simulation (Chapter 10) produced encouraging results with regards to achieving complex double curvatures using hollow GFRP tubes. GFRP has a desirable modulus of elasticity as well as flexibility in returning to their original positions, making them suitable for gridshell building. However, twisting movement of the GFRP tubes was restrictive. This requires further investigations to enable a good degree of torsional freedom which would bring about better deployability for increased double curvatures in the shells.

11.2.8 Concrete mix and reinforcement

The mix used in the experimental builds all used STRUX reinforcement fibres mixed within concrete. Different consistencies in concrete produced different quality surfaces for the exposed undersides of the concrete shell. The dryer mix produced heavily pockmarked surfaces in test shells 1 and 2 whilst the wetter and less viscous ones produced smoother finishes in test shells 3 and 4.

11.2.9 Reinforcements

All concrete used incorporated plastic reinforcement fibres (STRUX). In large scale construction, with the consultation of engineers, it will be imperative to incorporate reinforcement bars/ meshes of different material options e.g. carbon-fibre or glass fibre reinforced plastics to satisfy safety requirements/ building regulations. This is to be advised by collaborating structural engineers and statutory safety bodies.

11.2.10 Replication and appropriate development which are responsive to construction method

To repeat the use of formwork for reuse and be re-deployed, the construction of the 1:20 scaled model of the Downland gridshell (Chapter 10) raised the issue of curve continuation if the same mat was repeated. Using this new technology, the design may be modified to address the difficulty of creating a continuous curve in two or more parts. This can be overcome by articulation (i.e. separating the concrete shells completely) and glazing the spaces between concrete shells. This way, light can also penetrate the space beneath through these glazed gaps, similar to how Candela glazed gaps between component hy-pars to allow light to penetrate at the Capilla de San Vincente de Paul (1959) and other repeated hy-par umbrellas such as the Cayoacan market (1955).

11.2.11 Metal Sheets Gridshells produce flat shells

Although metal sheets were difficult to manipulate during gridshell construction, it produced evenly flat cushions (with a maximum thickness variation of 20mm ie 100% variation compared to 563% for Test Shell 1). The flat and wide metal plates of the gridshell allowed a different impression on the concrete which is largely flat to be achieved.

11.3 Construction

11.3.1 Gridshells can improve geometry definition

Test Shells 1,2, 3 and 4 have demonstrated the ability of the deployable gridshell to be more defined when pushed or pulled, and then restrained/ braced to create three dimensional shell formwork. This is very useful during casting to control/ accentuate/ adjust geometries to enhance shell action. This adaptability of adjustment makes for reusability, reconfigurability and structural intuition which other formwork systems cannot offer.

11.3.2 Deflection Control is paramount

Construction of shells in test shells 1 and 2 (Chapter 7), 3 (Chapter 8) and 4 (Chapter 9) indicated the flexible nature of the casting process. Gridshell movement is recurrent in all shell cases. The movement/ deflection of shells concrete affect the shape of the resultant concrete shell. Without vertical props to hold specific gridshell points in place, this may cause the shell to become asymmetrical (Test Shell 1, 2 and most obviously in Test Shell 4). Therefore, temporary propos need to support and monitor key points of the shell.

11.3.3 Minimises falsework and propping can check gridshell geometry during construction

The formwork was dynamic (i.e. constantly moving) as concrete was applied to the formwork (Chapter 7.2.1 and Chapter 9.3.1). In test shell 3, props were used to temporarily hold up the gridshell and control the formwork to ensure specific points are higher and prevent movement or asymmetry as a result of concrete application.

Test shells 1,2,3,4 and the final Downland simulation also showed that scaffolding and props can be minimized to reduce falsework use. It is however suggested that props that supported window openings or *resist impactos* may be supported by temporary scaffolding towers to act as height monitors during the erection of the formwork and during casting. Propping and supporting glass block windows may help to solve this problem in the real scale.

11.3.4 Comparison with existing shell construction methods

Table 11.1 updates table 3.2 with the 2017 Downland concrete gridshell simulation incorporated to give a comparison with other seminal concrete shells formwork system built since the beginning of the century. This table forms the basis of discussion under the headings of cost, form-freedom, shaping speed, reuse and recycle as well as surface qualities which are measures of concrete shell construction systems.

11.3.4.1 Cost

A comparison shows that the proposed system offers many benefits that past and contemporary methods could not. Although the system is perceived to be expensive at the outset, cost will reduce with each shell cast through formwork re-use. The thesis recognises the impact that cost has in a real and commercial building economy. Their ability to be re-used and re-configured reduces the cost in the life cycle of the deployable GFRP gridshell formwork. This is particularly useful in comparison with rigid curved timber glulam planks (Heinz Isler's shells), bespoke CNC milled foams or temporary OSB casting tables (used in Rolex Centre by SANAA and Kakamigahara Crematorium by Toyo Ito), as well as timber planks in Candela's shells.

11.3.4.2 Form-Freedom

Form-freedom offered by gridshells is increased by the fact that both proper and improper shells can be generated. Deployable gridshells form synclastic, anticlastic and monoclastic curvatures demonstrated by all test shells and the Downland simulation. Although the straight timber planks used by Candela had a high degree of expression, they required extensive scaffolding to support the timber plank formwork which this proposed system does not. Both earthforms and pneumatic forms suffer from bespoke and large degree of form monotony which does not apply to deployable gridshells formworks.

method	manual labour required	machining and tooling	costs	shaping speed	form freedom	surface quality	reuse of shaped element reuse	recycling of raw material
straight timber planks (eg Candela)	high,usually on site	very low-tech, readily available saws and nails	low	slow	large	variable (shuttering usually visible)	traditionally re-used	yes
glulam profiled sections (eg Isler)	high, on site or in factory	high-tech, bespoke mechanised	high	slow	limited, bespoke	high but depends on surface material	yes, if same shape	yes
CNC Milling of tables to form casting surface (eg.Rolex Centre)	limited, usually in factory for machine control	high-tech, bespoke and specialised	high	fast	unlimited	high but depends on surface material	not usually as bespoke but possible if same shape	yes
pneumatic formwork (eg Bini, Monoliths)	limited, during erection of inflatable shape	cutting patterns/ sewing/ bonding	moderate	fast	low, limited to controllable pneumatics	high	yes, if same shape	partially
concrete fabric formwork (e.g. West)	high, bespoke for each casting	cutting patterns/ sewing	low	fast	limited to controllable formfinding	high	yes, if for same shape	partially
pre-cast concrete elements (eg Nervi)	limited, due to repetition	repeated mould-making	low	N/A	limited to controllable formfinding	high, depends on finishing material	yes, if for same shape, but not usually	yes
earthmound formwork (e.g. Teshima)	limited with the use of mechanised equipment	large scale machines for moving earth	high	slow	no	depends on detailing	yes	partially
cable-stayed supported fabric formwork (eg Hi-Lo)	limited, bespoke and set up of cable-net and membrane	specialised machines	Low But design cost may be high	fast	limited to formfinding	high	partially	partially
Ctesiphon Vaulting Waller Shells	high, manual setting out of formwork and casting	hand applied and sprayed concrete low-tech and not specialist	low	fast	limited to vaults and domes	low, completed shells not thermally sealed	partially, not fabric	yes
deployable gridshell (eg Weald and Downland Concrete Shell, 2017)*****	limited with the use of mechanised equipment	preparatory drilling of GFRP gridlaths (but the formwork can be easily reused	high for the first cast, but with each re-use and re-configured application, cost per unit reduces.	fast (assumed 2 days in the scale of Cretail)	very within limits of elastic range of GFRP Can be used in both proper and improper shell generation.	flexibility of choice depends on chosen fabric texture	yes,	gridshell can be recycled, and reconfigured. Fabric formwork may not be able to be recycled but dependant on fabric formwork technology

Table 11.1 Comparison of formworks (adapted from Schipper, 2015)

11.3.4.3 Shaping Speed

This may be specific on an individual basis. However, a project such as the Creteil project (2012) was built with GFRP tubes took 10 people approximately a week to complete. A formwork created with GFRP is imagined to involve a similar amount of time to shape. Compared to Candela's labour- and material- intensive construction of timber bespoke formworks and Isler's glulam profiled sections, gridshells can offer a faster method of constructing doubly-curved formwork.

11.3.4.4 Surface Quality

Surface quality depends on numerous factors: concrete mix, casting technique and textiles type. This concern can be addressed through technology and construction knowhow. The need to vibrate concrete to smoothen after application (reduce blow holes and improve concrete quality) may however amplify deflection movements during the casting process and cause the concrete to slip away. This in turn may disturb eventual shell geometry. This may be overcome by the use of vertical props or supports that stabilizes the shell whilst vibration/ smoothing action was applied on the shell surface as suggested in Chapter 10.8.2.

11.3.4.5 Reuse and Recycle

The system is proposed with re-use in mind. Upon decentring, the gridshell could be re-configured or simply re-erected to the same form and prepared for casting concrete. When the system is not in use, they can be collapsed safely and be stored until the next application.

11.4 Performance

11.4.1 Structural Failure

Failure tests for Test 1, 2, 3 and 4 have shown the importance of geometry in the behaviour of concrete shells during loading. The way by which loads are transferred to the ground needs to be taken into account during the design stage.

11.4.2 Edges prone to high stresses

Free edges if the shells are prone to high stresses. This susceptibility is shown by test shells 3 and 4 displaying a high propensity to tear/ fissure at shell edges, suggesting that free edges constructed this way require reinforcements such as re-bars, or stiffening edge beam and/ or thickening shell edges as was reinforced in many of Heinz Isler's shells. Finite element analysis conducted for the Downland simulation (by ARUP) similarly confirms the stresses experienced by the free edges of the Weald and Downland concrete shell.

11.4.3 Light penetration and illumination uses

Test Shell 4 and Downland gridshell simulation model demonstrated methods of creating openings to allow light and air to penetrate a deep planned shell structure (Chapter 9.2.5). This was achieved through the use of *resist impactos* to create openings or by using pre-fabricated glazing blocks.

With the resultant concrete shell offering a large curved surface area of reflectance, various architectural atmospheres can be created (Chapter 10). Light entering at an oblique angle can be useful in picking up cushioning textures to form dramatic appearances. This is useful to the designer in constructing spatial tectonics.

11.4.4 Appearance expresses construction process

Test shells have resulted in highly expressive shell under-surface, clearly depicting the interaction of two key constituent ideas - firstly, fabric as formwork and secondly, deployable gridshell as a supporting frame. Impressions of gridshell formwork are highly expressed in the exposed underside with a distinct dominant appearance of the gridshell defined by the uppermost grid-laths. Showcasing the construction technique using different technologies, this proposed method demonstrates and supports stereogeneous idea suggested by Manelius (2012).

11.4.5 Impression of Shell thinness

Shell thinness is provided by thickness of shells visible at openings and edges. Two other factors result in the impression of thinness being the depth of cushioning and the height of the shell from the viewer discussed in Chapter 10.5. These factors need to be taken into consideration to create different effects/ appearance of concrete shell, should the perception of shell thinness be desired in the design.

11.4.6 Shell cast in two or more stages allow for shallower cushions

The Downland simulation (Chapter 10.6) shows that by carefully casting in 2 stages, a shell with shallower cushions can be achieved. Therefore, with casting the shell in 2 stages, it is possible to create a thin shell with low thickness variation to help achieve the perception of visual thinness. This process is also supported by the results of calculated FE analysis carried out by ARUP for the Downland simulation.

11.4.7 Structure

Failure tests for Tests 1. 2, 3, 4 all demonstrates the vulnerability of shell edges, suggesting the shell edge reinforcements. All shell edges experienced structural failure first. Failure testing in Chapter 7, 8 and 9 proved that edges of concrete shells constructed using this method were most vulnerable to initial failure.

Tests 1 and 2 have shown that shells (without cantilever edges) cast this way can be very strong with high failure loads. Test 1 has a failure load to self-weight ratio of 393% whilst Shell 2 has a ratio of 432% (Chapter 7.4.3.3). FEA (by ARUP) has confirmed the 2 stage casting being optimal for achieving a shell of 100mm overall thickness in the case of the Weald and Downland gridshell (Chapter 10.6.3). A first cast on fabric formwork supported by deployed gridshell can construct a self-supporting shell digitally found to be sufficiently strong for additional loading of sprayed concrete at 80mm. This allows cushions to remain shallow, hence creating a more efficient concrete shell (with less deadweight), imparting a visual perception of shell thinness. The FEA identified the first 20mm layer requiring metal mesh reinforcements (96mm2 of reinforcement/ metre equivalent to 5mm diameter bars at 200mm centres) whilst the top 80mm concrete layer does not require re-bar mesh although re-bar extenders from mesh is recommended to stitch both layers together for structural unity.

Erection process for this project envisaged the gridshell to be pushed upwards with PERI-UP system whilst being crane lifted. Individual scaffolding towers support glass block windows or *resist impactors* together with the gridmat. Their application serve two purposes: firstly, it acts as a monitoring device to check for point movements and ensure that formwork does not move excessively during casting. Secondly, it supports glass block windows or *resist impactos* which can be heavy.

FEA confirms shell of a depth of 100mm is possible for a shell cast over the GFRP Weald and Downland gridshell as formwork with a widest span of 16m and tallest height at 9.5m.

All test conducted on concrete shells and recorded during their construction strongly suggest this construction as a possibility to be developed further to erode the reasons why concrete shells are no longer built. Structural analyses and model construction simulation, process analysis of concrete shell construction using this method has verified this innovative approach.

11.4.8 Comparison with existing concrete shell performance

The body of work carried out in this inquiry allowed efficient (pure) and impure (bending) gridshells to be used as concrete formwork. In the case of the Downland simulation, a concrete shell of 100mm thickness is achievable. In the case of improper shells, with the help of structural engineers, this could be designed to counteract bending stresses through geometry change or re-bar reinforcements. However, the bespoke nature/ requirement of each design scenario must be respected and would require engineering expertise.

The table below is revised to incorporate the Downland concrete shell simulation to provide a comparison with seminal concrete shells built since the Jena planetarium in 1922.

project	Year complete	designer	formfinding	formwork	span	rise	thickness	Reinforcement details (if known)
Jena Planetarium	1922	Frank Dischinger	Mathematical	Metal geodesic dome	25m	12.5m	60mm	Wire mesh sacrificial
Leipzig Market Hall	1929	Hubbert Ritter (architect) Frank Dischinger And Dywidag	Mathematical And a 1/6 scale model	Zeiss-Dywidag method Gunnite on steelbar framework	65.8m (roof)	-	90mm	-
Zarzazuela Hippodrome Madrid	1935	Eduardo Torroja	Paper model and Mathematical	Timber boards	13m	-	50mm	Tensile steel reinforcement
Fronton Recoletes Madrid	1935	Eduardo Torroja	Physical Model, mathematical analysis	Timber boards	32m wide 55m long	-	80mm thick but at intersections 150mm	Thickening of concrete where the two vault beams intersected.
Cosmic Ray Pavilion	1951	Candela	mathematical	Timber boards supported by scaffolding	12m	5.5m	15mm	Steel 1/8 inch diameter wire placed 4 inches
Xochimilco Los Mantiales	1958	Candela	mathematical	Timber boards supported by scaffolding	42.4m roof 32.4m supports	5.85m centre	40mm	Stiffening Steel at groin
CNIT	1958	Nicolas Esquillan	Mathematical	Timber boards	218m	46.3m	65mm	Steel rods
Bubble Shells	1964 onwards	Heinz Isler	Physical Model, mathematical analysis	Timber boards	22m x 22m 54.5m	varies	varies	Steel mesh
Sicili Shell	1969	Heinz Isler	Physical Model, mathematical analysis	Timber boards and cross-laid strips	58m	8.75m	100mm	mesh
Duxford Aircraft Museum	1997	Foster and Partners	digital	Pre-cast concrete panels	90m	Min 16m	-	Rebars and precast concrete panel
Grin Grin Park (consists of 3 shells)	2006	Toyo Ito/ M Sasaki	digital	Timber boards	190m	50m	40mm	Mesh reinforcement
Kakamigahara Crematorium	2005	Toyo Ito/ M Sasaki	digital	Plywood tabled section blocks at 1m intervals	80m	60m	200mm	mesh
Rolex Learning Centre	2010	SANAA/ M Sasaki	digital	Timber tables	92m and 60m	varies	600mm	Steel rods normal diameter 19mm Hollow slabs
Teshima Art Museum	2010	SANAA/ M Sasaki	Digital	Earthmound	41.2m	5.12	250mm	Mesh reinforcement
Downland Concrete Shell *	2017	Cullinan proposed by Tang,2017	Digital and Physical Models (Chris Williams)	Deployable Gridshell	16m (max)	9.5m (max)	100mm cast in 2 layers	re-bars within preliminary 20mm concrete.

Table 11.2 Key concrete shells designed and built in the 20th Century showing the span, rise and relative shell thickness

The Downland concrete shell used a combination of digital and physical model in an iterative design process to not only create an efficient shell form, but a construction system which address reasons why concrete shells are not built any longer. Covered with fabric, it was enveloped with a preliminary concrete coat embedded with steel mesh. Following that, an additional 80mm of concrete was applied over this hardened shell.

In visual terms, the result expressed the use of the deployable gridshell as formwork clearly declaring the construction process (Pedreschi 2008). The formation of cushioning and indentations, including dominant lines of the formwork all record the process of shell formation. This stands in stark contrast to the Kikimigahara Crematorium roof (2006) erased all evidence of its formation, dematerializing concrete which was smoothed and painted white. This construction method allows the identity of concrete to be addressed, although it also offers an opportunity to dematerialize by rendering over the surface to achieve a polished surface.

11.5 Limitations of the research

- Although concrete cushioning may be attractive, their particularity in aesthetics may not be applicable to every project. However, this may be controlled by the type of fabric used or/ and how tightly they are stretched across the gridshell.

- Finite element analysis of the Downland simulation did not consider cushioning but assumes a smooth replica of the shell. It did not also take into account openings or loading of block windows and assumed the surface to be smooth i.e. without cushioning. Therefore, a more detailed model may be an area to develop this better.

- Adjusting the grid size will change the bending ability as a mat. This will also have an impact on the patterns that result: Smaller grids will produce smaller cushioning which would change their aesthetics and resultant shell strength and buckling behaviour altogether.

- Concrete is always applied from the top. This means that expensive cranes or scaffolding will be required to offer temporary support and lifting. Hence, the requirement for sophisticated machinery and construction safety may raise project costs. It is interesting to note that

- The large scale application of this technique and application at a building scale is an important aspect to test out the idea.

11.6 Recommendations and Future Work

Whilst this research has proved the possibility of building concrete shells using gridshells as temporary formwork, it has importantly uncovered related research strands, particularly in the fields of engineering, analysis and construction. This body of work has sowed the seeds of avenues of further investigations.

These will be outlined in three main headings: namely the gridshell formwork, the casting process and the resulting concrete shell.

11.6.1 Gridshell formwork performance:

- Due to limited resources, scale is an unanswered aspect: further research could examine the idea of size limits of this system. Although all four test shells were constructed this may form a useful preliminary guideline to test out the construction at a building scale. Other questions related to this include the size of glass fibre tubes, and joints to be used and the effects of different grid configurations in the assembling of the gridmat and possibly the mechanization of gridmat manufacture in the commercial factory.

- Gridshell nodes: In the prototypes, thin metal wires were used to connect laths together. A more suitable and more secure method of connecting the laths together could be investigated and developed. In Creteil and Solidays projects (Du Peloux et al 2015, Baveral et al, 2012), with generous sponsorship from commercial partners, they were able to use sophisticated swivel connectors which are expensive and specialized. A cheap and readily accessible and intuitive joint could be further developed.

- Fabric design needs to be taken into account when this method is used in a larger scale. Seen by the basic testing on FEM and construction, the cushioning provides additional strength to the structure. The degree of drape and amount of fabric usage is a relevant aspect to investigate further. The possibility of leaving the fabric on the surfaces of the concrete for insulative or acoustic purposes can be investigated further in textile technologists.

11.6.2 Casting Process:

- The control of process and the control of concrete evenness, shape and smoothness are important aspects to consider.
- The mechanization and speeding up of the trowelling process will be facilitated by spraying concrete onto the fabric surfaces in thin layers. A technology commonly applied to tunnelling and engineering work, this aspect must be experimented and researched further on the technicalities and to evaluate the cost and time saving of such a system. The Sprayed Concrete Association has expressed confidence in this proposed method.
- The development of specialized concrete mix with insulative or structural properties, and different mixes for different layers could be further explored. For example, high-quality rapidly setting concrete may be used for the first cast layers to be stronger; lighter weight concrete material e.g. vermiculite may be used for subsequent upper layers.
- A series of scaffolding or airform pneumatic support design may be required. As such further development of hybridized methods of construction as investigated fundamentally can be tested and researched further.

11.6.3 Concrete shells

- Although the cushioning are treated as deadweight, the effects of cushioning patterns on the buckling behaviour of these shells are an important aspect particular to this technology deserving further investigation. The effects of cushions and corrugations (similar to Waller's shells) in terms of buckling and effective thickness require further structural/ numerical investigation with structural engineers.
- The physiological aspects and subjective perceptions i.e. qualitative values of shells provide interesting scope for investigation. These will involve the analysis, both qualitatively and quantitatively in terms of illuminance and acoustics offered and created by these concrete shells with an undulating patterning.
- Further form expressions. The quest for forms other than ruled geometries or hyperbolic paraboloid also requires further investigation.
- The 4 shells are consistently anchored at 2 points; variation of edges and abutment variation could be trialled and tested. The treatment of shell open-ends and free-edges are also important aspects of exploration with respect to structural and visual thickness.

11.6.4 Insulation and roofing finishing

- Concrete shell structures are monolithic. When constructing in colder climates, insulation needs to be installed. Potentially, the fabric may incorporate insulative properties that help increase thermal performance of the shell material. The fabric may also be embedded within the concrete and left in situ. Another idea may be to cast lightweight and insulative concrete for outer layers.
- Insulation could also be added or woven into the fabric and the fabric left in place, in the casting. Further investigations into creating an insulative fabric can be explored.

11.7 Concluding Remarks:

The original contribution to knowledge is the introduction of a new method/ system of constructing concrete shells using deployable gridshells as formwork. This adds to existing methods and technologies by examining the reasons why monolithic concrete shells are not as popularly used today compared to the past.

Since this idea was first presented at the 2012 IASS conference in Seoul, South Korea (Tang, 2012) and ICFF Bath (Tang, 2012), this has attracted academic interest from the scientific community. It is encouraging also that since attendance at the presentation (Tang and Pedreschi, 2015) given by the author at 2015 ICFF/ IASS presentation in Amsterdam, Cuvilliers, Douthe, du Peloux and Le Roy (2017) from École des Ponts Paris Tech , Paris have begun experimenting with this idea.

Co-ordination and Collaboration intensive system

The use of this system, like any shell projects, requires intensive co-ordination between architect, structural engineer and builder. Although material is not expensive, specialist design have the propensity to inflate project cost compared to alternative more "straight-forward" systems such as steel frame constructions. Although concrete shells made from gridshell formwork may be attractive in many ways, it is important to evaluate their appropriateness and tectonic merits on an individual project basis.

Re-configurable system

Gridshell as formwork is an exciting innovation. The experiments have proved gridshell formwork to be reconfigurable where sections joined up to form bigger mats that could be completely taken apart to be re-fastened/ re-connected / re-formed to make new gridmats for new shells. This quality imparts flexibility/ repeatability where gridmats of different shapes and sizes could be created.

Actively-bent physical models can help the designer to design shell structure initially.

Being intuitive and physical, the deployable mat model can help the designer to initially think and visualize space and not dismiss concrete shells as an architectural option at the first instance.

The gridshell is visually transparent, (see-through due to grid arrangements). As such, it allows the designer to develop an understanding of the spaces that the resultant shell would enclose.

This piece of research is not restricted to a novel method of construction using existing materials and existing construction ideas, it encompassed a hands-on, tangible collaborative approach to develop, invent, materialize and realize a constructional idea. It stresses a holistic yet pluralistic respect and integration of different technologies to cross-fertilize, share, innovate and collaborate with other professionals such as engineers and builders. The research has combined many ideas such as technology, process and tectonics to produce creative interventions to update the design and construction of a seemingly defunct building typology.

The body of work verifies and validates this novel innovation of using deployable gridshells as concrete shell formwork, re-discovered through a series of experimental student workshops. The PhD fills a gap in designing and building shells. By using deployable gridshells as a response to the social, economic and technical understanding to why shells are not built anymore, this research reaffirms the feasibility of this application setting an exciting and significant start to further practical potentials of this new field of concrete shell building.

Detail, Downland Shell, 2017 (Gabriel Tang)

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APPENDICES

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This relates to Chapter 7: VERIFICATION OF HYPOTHESIS

Appendix A: Height measurement

Shell 1

	x (mm)											
y (mm)	0	25	50	75	100	125	150	175	200	225	250	275
0	867	862	859	855	853	853	850	845	847	847	847	845
25	835	826	822	819	820	821	820	817	820	820	822	820
50	804	793	791	791	789	793	790	788	791	793	797	794
75	770	762	760	762	762	764	762	762	765	767	768	767
100	742	733	734	735	736	740	738	737	742	742	746	744
125	712	706	706	710	713	717	716	715	718	720	722	723
150	683	681	684	687	690	693	693	692	693	698	702	701
175	658	656	660	665	667	670	669	670	672	676	680	678
200	632	631	634	639	643	647	649	647	651	655	659	658
225	606	604	608	614	620	623	624	624	628	631	634	635
250	580	579	584	586	594	600	599	600	604	607	612	611
275	557	556	560	564	568	575	577	576	580	583	586	587
300	535	534	539	541	544	550	552	553	558	560	565	563
325	513	513	517	519	522	527	529	530	534	537	541	539
350	495	496	498	500	503	508	509	510	513	516	518	517
375	480	480	482	485	486	490	490	491	493	496	499	496
400	467	466	468	470	471	474	474	474	477	479	481	478
425	453	453	456	455	457	458	459	459	460	461	463	461
450	441	440	442	443	444	445	445	445	445	444	446	446
475	430	429	431	431	431	433	432	432	433	432	433	431
500	420	419	419	420	420	422	422	420	420	421	421	419
525	410	408	409	409	410	411	411	409	409	409	409	407
550	402	401	401	401	402	402	402	400	400	400	400	398
575	394	393	392	393	394	394	393	392	391	391	391	390
600	387	386	386	386	387	387	386	385	385	385	385	383
625	382	380	380	381	381	381	381	380	379	379	380	379
650	377	376	376	375	377	377	377	376	376	376	376	375
675	374	373	373	373	374	374	374	373	373	373	374	373
700	373	372	372	372	372	372	373	373	373	373	372	373
725	374	373	373	373	374	374	374	375	374	374	374	373
750	375	374	374	375	376	375	377	378	377	377	376	376
775	378	377	378	378	379	379	381	381	381	381	379	380
800	384	382	382	382	383	384	385	386	386	385	385	384
825	389	387	387	387	389	388	390	391	390	390	389	389
850	394	393	394	394	395	396	396	397	397	397	396	397
875	401	400	402	401	403	403	405	405	406	405	405	405
900	408	409	409	410	410	412	413	415	415	415	414	416
925	417	418	418	419	421	421	424	426	425	425	426	429
950	426	427	428	429	432	432	435	437	438	439	439	443

975	436	438	439	440	443	445	449	451	451	454	454	457
1000	447	449	452	454	456	459	463	466	468	470	469	472
1025	463	464	466	469	479	475	481	484	485	487	487	491
1050	481	482	485	486	492	493	499	506	507	507	507	513
1075	502	505	506	509	515	515	521	528	531	533	531	538
1100	523	526	530	531	537	539	546	555	557	557	558	566
1125	546	548	552	557	569	565	571	581	584	584	585	593
1150	571	574	581	585	593	593	599	609	613	614	615	623
1175	601	607	612	616	623	626	633	642	645	644	647	652
1200	629	638	641	645	653	655	662	670	671	673	674	681
1225	662	669	675	678	684	685	693	702	704	706	707	713
1250	700	702	707	711	714	718	723	730	730	732	732	741
1275	735	738	740	740	743	743	749	757	758	759	760	766
1300	775	774	772	773	777	776	782	790	790	787	788	793
1325	819	809	805	806	808	810	815	817	822	818	817	821
1350	860	850	846	841	844	843	846	849	851	846	846	847

		x (mm)											
		300	325	350	375	400	425	450	475	500	525	550	575
y (mm)	0	846	842	844	843	845	846	843	848	850	850	849	850
	25	820	818	820	822	820	823	823	825	826	824	824	825
	50	797	795	797	799	798	800	800	798	801	801	801	802
	75	772	771	774	774	775	774	776	776	777	777	775	776
	100	748	748	750	752	751	752	751	751	751	748	750	749
	125	725	726	727	729	727	726	728	726	726	726	727	726
	150	702	703	704	705	705	704	705	704	705	704	705	702
	175	679	680	682	682	683	683	683	683	682	682	682	681
	200	659	657	659	660	660	661	660	659	658	659	657	658
	225	635	635	636	635	637	636	636	637	635	635	634	631
	250	612	610	610	611	610	610	611	610	611	611	608	608
	275	587	586	585	586	586	586	587	587	589	588	586	585
	300	563	561	561	562	562	556	563	564	564	563	562	561
	325	538	535	536	537	539	539	540	541	538	539	538	536
	350	516	515	515	516	516	518	518	519	519	518	517	512
	375	496	495	494	495	495	496	498	498	499	498	494	492
	400	478	476	476	474	476	476	478	476	478	477	475	472
	425	460	459	458	458	458	459	459	460	460	458	455	454
	450	444	443	441	442	441	442	442	442	442	442	438	435
	475	429	428	427	427	427	427	427	427	426	426	424	421
	500	417	416	415	415	415	415	415	416	414	413	411	409
	525	407	405	404	404	404	404	404	404	403	402	399	397
	550	397	396	396	396	396	396	396	395	394	392	391	389

	575	389	388	388	389	388	388	387	386	385	384	382	380
	600	382	381	382	382	382	381	380	380	377	377	376	375
	625	377	377	377	377	376	376	375	374	373	372	371	369
	650	374	373	374	374	374	373	373	372	370	369	369	366
	675	373	372	373	373	373	372	371	371	369	368	367	365
	700	372	373	372	372	372	372	370	369	365	368	367	365
	725	373	373	373	374	373	372	371	371	370	369	369	368
	750	374	374	374	375	375	374	374	375	374	373	373	371
	775	379	378	378	379	379	379	377	379	380	379	378	377
	800	383	383	384	384	385	385	385	385	386	386	386	384
	825	389	389	391	391	392	392	393	393	394	394	394	394
	850	396	397	398	399	400	401	401	402	403	404	403	404
	875	406	407	408	409	409	410	412	412	414	414	416	417
	900	418	419	420	421	422	422	424	425	426	428	428	430
	925	430	432	434	435	437	438	440	441	442	442	443	445
	950	444	446	448	450	452	454	455	455	458	458	460	460
	975	459	461	464	466	469	470	472	474	475	476	477	477
	1000	476	478	482	483	486	489	491	492	495	494	497	496
	1025	494	498	502	505	508	509	512	515	516	516	519	518
	1050	515	521	525	528	532	533	536	537	540	540	542	541
	1075	541	547	550	554	558	559	562	564	567	568	567	570
	1100	569	575	579	580	584	587	589	591	593	595	596	595
	1125	596	602	606	608	613	615	619	618	621	622	622	622
	1150	625	632	635	637	641	643	645	646	648	650	649	649
	1175	656	663	667	668	670	672	676	675	677	679	677	677
	1200	687	693	697	696	698	699	701	702	703	703	703	702
	1225	716	723	725	725	727	727	729	727	727	728	728	727
	1250	742	747	750	750	752	751	752	751	753	752	752	751
	1275	766	772	776	774	775	776	778	775	777	777	777	776
	1300	796	801	806	802	803	803	807	803	803	803	804	803
	1325	822	827	829	828	829	829	830	828	828	830	828	829
	1350	849	853	856	855	856	854	856	854	853	855	854	852

		x (mm)											
		600	625	650	675	700	725	750	775	800	825	850	875
y (mm)	0	848	847	847	844	840	845	843	847	851	856	856	865
	25	823	824	824	821	821	818	817	819	821	824	821	826
	50	800	799	798	796	795	794	793	794	794	795	792	795
	75	775	774	774	771	771	769	766	767	766	766	762	761
	100	750	748	747	744	743	743	740	740	738	737	731	729
	125	725	723	723	719	719	717	714	716	712	708	700	697

150	702	702	699	694	692	691	687	686	686	680	674	666
175	680	678	674	671	669	665	661	659	659	652	645	638
200	655	653	649	646	642	639	633	631	627	621	613	611
225	630	627	624	621	616	611	605	603	597	593	586	584
250	605	603	599	595	589	584	579	575	569	564	559	556
275	582	579	575	571	565	559	554	551	544	538	533	532
300	557	554	549	545	538	534	529	528	521	516	512	511
325	533	528	524	519	514	512	508	506	500	496	492	490
350	509	505	500	497	493	491	487	486	481	477	474	472
375	487	485	480	478	473	471	467	466	463	459	456	454
400	468	465	462	459	455	453	450	449	446	443	440	439
425	450	447	444	441	438	436	433	432	429	428	425	425
450	432	430	427	425	422	419	417	416	415	413	411	412
475	419	415	413	411	408	406	404	403	403	402	400	401
500	407	403	400	398	396	395	393	392	392	390	390	391
525	395	392	389	387	385	384	382	383	382	382	383	384
550	386	384	382	380	378	376	375	375	375	374	374	376
575	378	376	375	373	371	370	369	368	368	367	369	370
600	372	371	370	369	367	365	363	363	363	363	363	366
625	368	367	365	365	364	363	361	359	359	358	360	361
650	365	363	363	363	362	360	359	358	357	357	357	359
675	364	363	363	362	361	360	359	358	357	357	357	358
700	364	364	364	364	362	361	360	359	359	358	358	359
725	367	366	366	366	364	364	364	362	362	360	361	363
750	371	370	369	369	369	368	368	367	367	367	366	368
775	376	376	375	374	374	373	374	373	374	374	373	375
800	385	384	383	384	383	382	383	382	382	382	382	383
825	395	393	394	395	394	392	393	391	391	391	391	391
850	406	406	406	407	406	404	405	402	402	402	402	402
875	418	419	419	420	418	416	417	415	414	413	413	413
900	431	432	433	433	431	430	430	428	427	427	426	425
925	447	447	447	448	447	444	444	442	441	441	440	440
950	462	463	463	463	462	459	458	456	455	456	454	453
975	480	480	481	481	481	477	476	475	474	472	470	468
1000	497	498	499	501	500	498	497	493	492	490	488	486
1025	517	520	520	521	521	520	518	514	513	510	506	505
1050	544	543	542	543	544	542	541	535	533	532	527	524
1075	571	570	570	571	569	566	566	561	558	554	550	547
1100	597	599	597	598	595	593	592	586	583	579	575	572
1125	625	626	624	623	622	616	617	610	608	608	603	598
1150	651	652	651	649	648	644	644	638	635	631	632	626
1175	678	679	681	677	675	672	671	668	664	662	661	655
1200	704	704	703	703	703	700	697	695	692	687	687	684

	1225	728	728	729	729	729	726	725	720	719	718	716	713
	1250	754	753	754	752	753	751	752	749	747	747	743	744
	1275	779	777	777	776	777	776	777	776	777	776	773	773
	1300	805	803	805	802	803	805	805	803	804	803	803	807
	1325	831	829	829	827	828	826	827	825	827	827	829	836
	1350	855	853	853	852	851	854	854	854	858	860	860	866

SHELL 2

		y (mm)									
		0	25	50	75	100	125	150	175	200	225
x (mm)	0	872	857	855	847	843	844	841	843	845	842
	25	833	819	815	812	811	808	806	808	805	805
	50	785	775	773	777	778	779	776	776	776	779
	75	744	742	744	746	750	751	748	749	750	749
	100	710	708	713	714	715	720	720	720	721	724
	125	669	670	673	679	684	687	687	688	692	692
	150	633	634	637	642	648	653	654	656	660	660
	175	600	600	605	607	615	624	621	624	625	628
	200	566	566	572	579	585	590	590	595	596	598
	225	530	532	539	546	554	558	561	563	567	569
	250	501	502	509	515	523	531	531	535	537	539
	275	471	475	482	489	496	501	503	507	508	512
	300	445	449	453	462	466	472	479	478	480	483
	325	420	423	430	437	440	446	448	450	452	454
	350	400	404	408	414	418	422	424	424	426	428
	375	382	385	388	391	395	400	401	401	403	404
	400	364	367	368	373	374	377	378	379	381	382
	425	347	349	349	354	355	358	358	359	360	360
	450	331	332	333	336	338	340	340	341	343	344
	475	316	316	318	321	322	324	324	327	328	329
	500	305	304	306	308	309	310	311	313	314	315
	525	295	295	296	297	298	299	299	301	302	302
	550	289	288	288	290	290	291	291	291	292	292
	575	283	282	282	282	282	283	282	283	284	284
	600	278	277	277	277	278	277	276	277	278	278
	625	275	274	274	274	273	274	273	274	274	275
	650	274	273	273	272	273	273	272	273	272	272
	675	274	273	274	274	273	274	273	273	273	272
	700	277	276	276	275	277	275	274	275	274	274
	725	281	280	279	279	278	277	277	277	277	276
	750	286	285	284	282	281	281	281	282	281	280

775	292	291	290	289	287	286	286	286	285	284
800	300	299	298	298	295	293	293	293	292	291
825	309	309	308	307	305	304	304	304	302	302
850	320	321	321	321	320	318	318	318	317	317
875	334	335	336	333	334	334	334	334	333	334
900	349	350	350	349	350	350	351	351	350	350
925	368	370	370	368	369	368	368	369	367	368
950	390	391	391	392	389	399	388	389	388	389
975	412	414	416	412	414	388	414	413	414	414
1000	436	438	440	437	438	412	439	438	439	438
1025	464	469	469	468	467	437	467	466	465	465
1050	495	496	498	495	495	467	497	496	494	494
1075	528	530	530	526	525	493	527	528	526	526
1100	565	567	566	560	557	523	559	559	557	556
1125	606	600	600	594	591	555	593	592	587	586
1150	647	639	637	630	628	589	629	623	622	618
1175	682	679	677	670	668	624	667	664	661	659
1200	718	718	710	703	699	698	698	696	697	695
1225	774	761	756	747	739	735	730	729	731	726
1250	816	806	800	788	782	773	771	770	771	770
1275	863	850	844	832	824	817	814	810	808	811
1300	883	879	877	869	865	855	854	853	852	852

		y (mm)								
		250	275	300	325	350	375	400	425	450
x (mm)	0	837	840	836	844	855	851	860	865	868
	25	807	806	803	811	815	819	822	833	846
	50	778	781	781	781	786	788	792	798	811
	75	750	753	754	755	759	757	762	766	774
	100	722	727	725	729	731	732	733	735	737
	125	694	694	694	699	701	704	703	705	704
	150	661	661	664	671	673	635	668	671	671
	175	630	629	631	640	641	604	640	639	638
	200	598	603	601	607	603	575	606	608	609
	225	569	570	579	576	574	544	576	577	574
	250	539	544	545	544	544	516	544	545	546
	275	512	516	517	516	514	486	514	513	511
	300	484	485	487	490	487	458	485	484	484
	325	456	458	458	459	459	433	458	458	456
	350	430	429	432	434	433	408	433	433	429
	375	404	408	409	410	413	386	409	408	408

	400	382	384	386	386	387	367	385	387	386
	425	360	363	364	365	368	350	369	368	368
	450	344	346	347	349	350	336	351	351	351
	475	330	332	334	335	335	321	336	337	336
	500	315	318	319	320	322	310	324	324	322
	525	303	304	306	307	309	301	312	312	312
	550	293	294	296	298	300	293	303	303	303
	575	285	285	288	289	291	286	294	265	295
	600	279	281	282	283	285	280	286	287	274
	625	275	276	277	278	279	275	280	280	280
	650	273	274	274	275	274	272	275	275	276
	675	272	273	273	273	272	272	273	273	273
	700	273	273	274	273	272	273	272	272	273
	725	275	276	275	276	274	278	273	273	273
	750	279	280	280	280	278	283	277	277	276
	775	285	284	284	285	283	290	282	282	282
	800	291	291	291	291	290	299	290	290	288
	825	302	301	300	299	299	311	299	299	298
	850	316	316	314	314	311	325	309	309	308
	875	333	332	329	329	327	341	324	323	322
	900	349	348	346	345	343	358	339	337	337
	925	367	366	364	362	360	377	356	354	354
	950	389	386	384	382	379	400	375	372	372
	975	415	414	412	407	403	426	398	393	392
	1000	438	438	437	433	427	454	422	417	415
	1025	465	468	437	463	457	481	449	443	442
	1050	496	498	492	490	485	513	478	472	469
	1075	525	526	522	518	515	546	510	504	502
	1100	553	554	552	550	546	577	544	540	535
	1125	584	585	584	580	577	613	577	575	570
	1150	619	615	615	615	612	652	611	609	606
	1175	661	656	656	650	651	688	649	647	640
	1200	696	691	692	688	687	727	687	686	687
	1225	725	726	726	727	724	772	723	724	732
	1250	767	768	767	769	769	815	771	775	777
	1275	807	804	808	805	810	863	815	823	829
	1300	857	853	849	862	863		868	869	871

APPENDIX B: THICKNESS MEASUREMENT

SHELL 1

On indent lines			
x (mm)	y (mm)	thickness (mm)	Average (mm)
0	0	16,8	46,0
75	0	41,6	
125	0	43,5	
150	0	56,9	
275	0	55,2	
375	0	62,9	
475	0	51,2	
575	0	58,6	
650	0	47,4	
750	0	49,9	
875	0	21,7	
0	75	22,9	43,8
100	75	49,3	
175	75	48,2	
275	75	58,4	
350	75	49,1	
450	75	57,6	
525	75	46,6	
600	75	51,4	
700	75	39,0	
775	75	36,7	
875	75	22,6	
0	200	16,8	31,9
75	200	30,8	
175	200	42,6	
250	200	32,6	
375	200	39,2	
425	200	34,3	
525	200	39,7	
625	200	30,4	
700	200	36,7	
800	200	27,9	
875	200	20,4	
0	337,5	15,9	19,1
100	337,5	19,6	
175	337,5	16,5	
275	337,5	25,7	
350	337,5	16,5	

On cushions			
x (mm)	y (mm)	thickness (mm)	Average (mm)
0	125	21,3	39,2
25	125	32,1	
100	125	48,2	
200	125	44,3	
325	125	54,0	
375	125	43,6	
475	125	51,5	
575	125	43,3	
650	125	45,2	
750	125	31,5	
825	125	31,1	
875	125	24,3	
0	275	22,1	25,1
75	275	29,7	
100	275	25,7	
225	275	31,2	
300	275	22,8	
400	275	29,8	
487,5	275	19,3	
575	275	23,9	
675	275	19,8	
775	275	30,9	
875	275	21,2	
0	425	19,9	24,0
50	425	23,2	
150	425	29,8	
225	425	16,4	
325	425	27,0	
387,5	425	14,3	
475	425	21,6	
587,5	425	18,8	
675	425	35,2	
800	425	30,2	
850	425	30,6	
900	425	21,2	
0	600	23,6	28,5
100	600	27,5	
125	600	24,6	

450	337,5	24,3	
537,5	337,5	9,3	
625	337,5	23,3	
725	325	18,4	
800	325	21,3	
875	325	18,9	
0	500	17,2	
87,5	500	19,6	
175	500	21,4	
275	500	12,4	
375	500	22,3	
450	500	9,4	20,9
525	500	21,5	
650	487,5	21,5	
700	487,5	36,8	
825	487,5	27,1	
875	487,5	21,2	
0	675	21,8	
100	675	24,1	
175	675	22,4	
275	675	33,5	
362,5	675	20,0	
425	675	32,4	25,2
537,5	675	19,9	
625	675	34,5	
725	675	24,2	
800	675	25,6	
875	675	18,5	
0	875	20,9	
100	875	23,9	
200	875	29,2	
275	875	18,1	
375	875	33,7	
450	875	18,9	23,6
550	850	29,8	
650	850	13,6	
725	850	28,9	
825	850	22,1	
875	850	20,3	
0	1037,5	20,6	
100	1037,5	20,2	
175	1037,5	16,2	19,4
275	1037,5	24,3	
350	1012,5	12,2	
450	1012,5	23,4	

250	600	32,5	
325	600	23,2	
387,5	600	29,2	
500	600	19,7	
600	600	33,7	
700	600	30,0	
775	600	40,9	
875	600	28,3	
0	775	24,0	
125	775	32,1	
225	775	19,0	
325	775	32,3	
400	775	22,6	
475	775	33,0	27,9
625	775	24,7	
675	775	34,3	
775	775	27,9	
825	775	33,3	
875	775	23,8	
0	950	18,7	
75	950	26,6	
125	950	23,1	
225	950	28,5	
300	950	19,2	
450	950	24,8	23,6
525	950	16,1	
600	950	22,7	
687,5	950	20,0	
775	950	35,7	
875	950	23,9	
0	1100	22,2	
125	1100	27,6	
225	1100	17,7	
325	1100	26,2	
400	1100	20,2	
500	1100	27,3	23,2
600	1100	15,4	
675	1100	28,0	
775	1100	24,5	
825	1100	26,4	
875	1100	19,4	
0	1250	17,8	
75	1250	29,5	34,5
150	1250	30,4	
250	1250	37,3	

562,5	1012,5	11,4	
625	1012,5	23,8	
725	1012,5	18,5	
800	1012,5	22,7	
875	1012,5	19,8	
0	1162,5	20,2	
87,5	1168,75	21,5	
175	1162,5	30,4	
262,5	1162,5	18,9	
375	1150	30,9	
450	1150	21,9	25,1
525	1150	32,0	
625	1150	17,8	
725	1150	35,3	
800	1150	26,5	
875	1150	20,9	
0	1287,5	20,0	
125	1287,5	37,7	
175	1287,5	38,7	
250	1262,5	43,0	
350	1262,5	39,3	
425	1250	44,6	36,3
525	1262,5	41,9	
600	1262,5	46,2	
700	1262,5	33,7	
775	1262,5	34,3	
875	1262,5	19,6	
0	1350	29,4	
125	1350	52,9	
225	1350	50,9	
325	1350	52,6	
387,5	1350	56,5	
450	1325	61,6	48,2
575	1325	53,0	
675	1325	58,3	
750	1350	52,3	
800	1350	42,2	
875	1350	20,0	

337,5	1250	35,9	
425	1250	43,0	
525	1250	42,7	
600	1250	47,9	
700	1250	36,5	
775	1250	35,0	
875	1250	24,0	

SHELL 2

On indent lines			
x (mm)	y (mm)	thickness (mm)	Average (mm)

On cushions			
x (mm)	y (mm)	thickness (mm)	Average (mm)

0	50	43,4	
0	100	49,6	
0	150	60,5	
0	200	59,4	55,1
0	275	66,9	
0	325	59,5	
0	375	58,3	
0	425	43,6	
50	0	25,4	
75	75	36,9	
75	125	44,5	
75	175	44,0	
75	225	52,1	41,7
75	300	50,0	
75	275	48,8	
75	350	48,0	
75	400	38,8	
75	450	28,2	
175	75	31,4	
175	125	23,8	
175	175	33,2	
175	225	29,1	29,0
175	275	32,3	
175	325	28,2	
175	350	25,3	
300	50	17,3	
300	125	20,1	
300	175	15,9	
300	225	23,0	19,0
300	275	16,4	
300	350	20,7	
300	400	19,6	
450	50	26,4	
463	113	15,1	
463	175	26,9	
475	225	15,7	20,6
475	281	24,6	
463	325	13,1	
475	400	22,3	
650	58	13,4	
650	113	23,8	
663	163	17,6	18,6
663	225	27,2	
663	275	14,5	
669	325	20,8	

25	0	21,5	
25	50	37,3	
25	100	45,2	
25	150	59,8	
25	200	58,4	48,9
25	250	65,3	
25	325	62,0	
25	375	63,8	
25	425	44,8	
25	450	30,5	
125	0	20,4	
125	100	30,1	
125	150	30,6	
125	200	36,4	30,4
125	250	33,9	
125	325	34,6	
125	375	29,2	
125	450	27,9	
225	0	18,1	
225	50	21,4	
225	100	18,2	
225	150	23,2	
225	200	21,7	21,5
225	250	24,3	
225	325	20,9	
225	400	24,4	
225	450	21,1	
375	0	18,9	
375	50	21,1	
375	100	21,9	
375	150	16,6	
375	200	22,9	20,5
375	250	18,3	
375	312,5	22,4	
375	387,5	18,2	
375	400	25,5	
375	450	19,1	
500	0	22,0	
500	37,5	35,9	
500	100	23,2	
500	175	31,7	25,5
500	225	22,5	
500	275	30,2	
500	325	21,0	
500	375	27,1	

675	375	13,4	
663	425	18,3	
850	63	24,9	19,2
850	125	17,7	
856	175	22,1	
856	225	10,9	
863	288	21,3	
856	331	14,0	
869	388	23,7	
1000	38	15,0	17,5
1013	75	13,3	
1013	131	21,8	
1013	175	17,5	
1013	238	24,4	
1013	281	13,3	
1018	338	20,1	
1025	388	14,8	
1125	63	31,7	33,9
1138	125	32,3	
1138	175	40,1	
1138	238	36,3	
1144	288	42,5	
1144	338	34,1	
1150	400	33,3	
1150	450	21,2	
1238	50	36,5	45,6
1238	75	40,0	
1263	138	54,8	
1250	188	49,4	
1263	238	58,4	
1256	300	48,7	
1250	350	52,5	
1250	400	42,0	
1250	450	27,7	

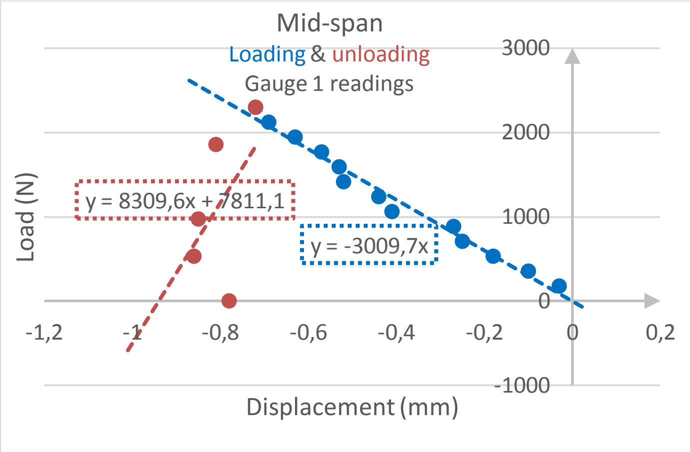
500	450	16,3	
775	0	26,5	26,0
775	25	27,9	
775	75	33,8	
775	137,5	25,9	
775	200	30,0	
775	250	22,3	
775	300	28,1	
775	350	21,3	
775	400	24,6	
775	450	19,1	
925	0	24,3	27,8
925	75	29,0	
925	100	20,0	
925	150	26,0	
925	200	27,6	
925	250	32,0	
925	312,5	32,0	
925	375	46,3	
925	450	12,9	
1075	0	18,8	24,9
1075	100	32,2	
1075	162,5	25,6	
1075	225	27,4	
1075	250	24,4	
1075	300	26,8	
1075	350	23,5	
1075	450	20,8	
1175	0	29,9	44,7
1175	75	41,0	
1175	112,5	42,5	
1175	162,5	52,8	
1175	225	55,1	
1175	262,5	60,2	
1175	300	53,1	
1175	375	51,4	
1175	450	16,7	
1275	25	28,2	45,1
1287,5	100	53,1	
1287,5	162,5	49,8	
1287,5	187,5	60,2	
1275	275	54,1	
1275	350	53,1	
1275	387,5	39,8	
1275	450	22,2	

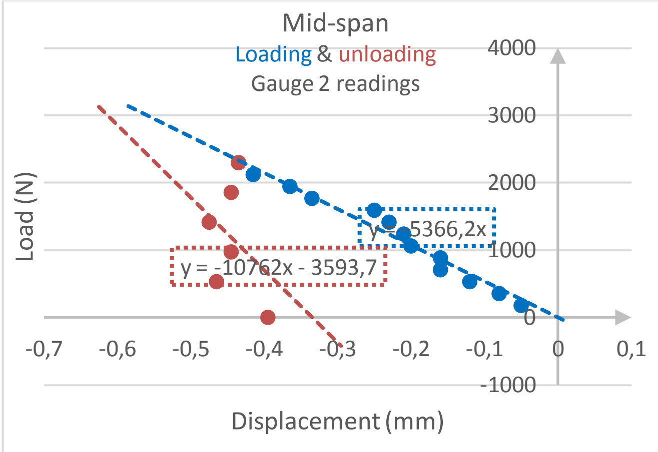
Appendix C: Static loading testing

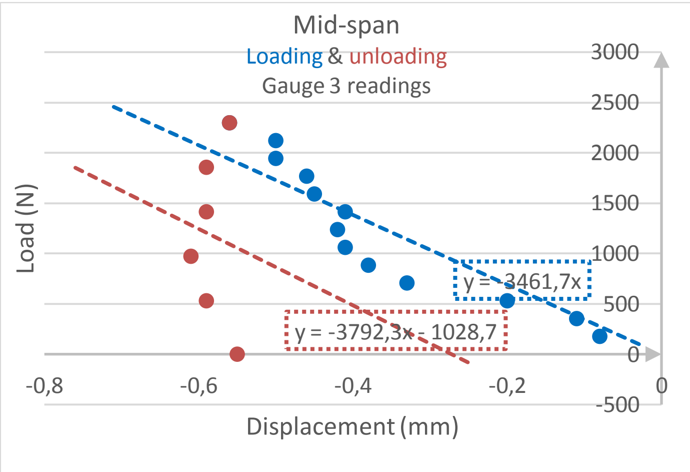
Shell 1

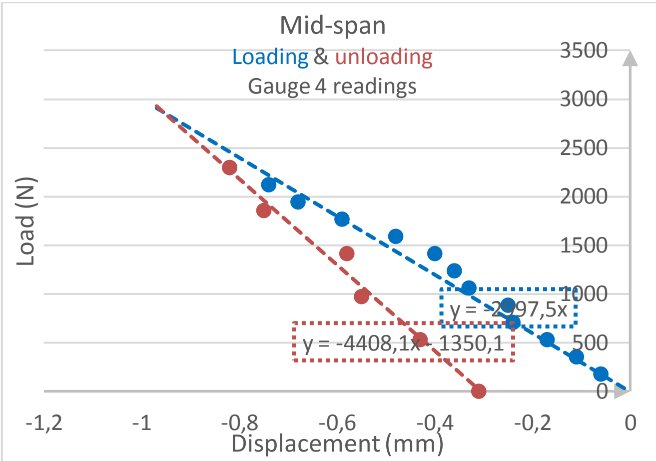
Midspan loading

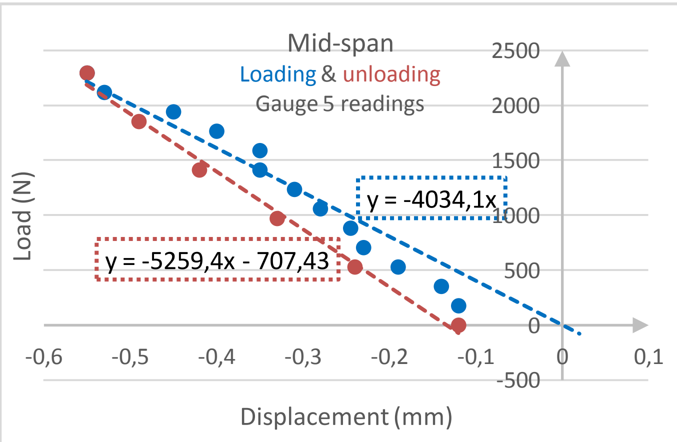
Table C1

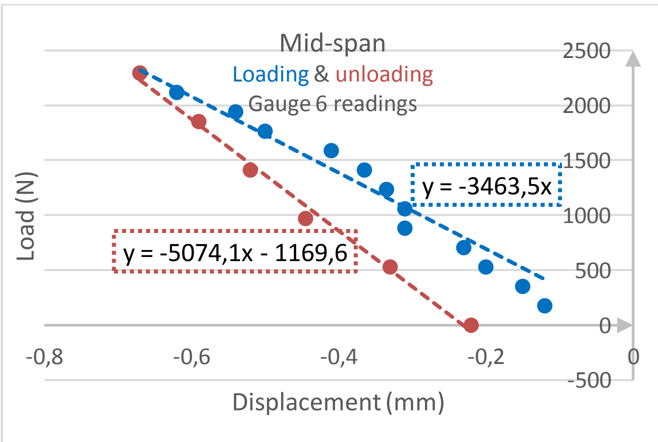


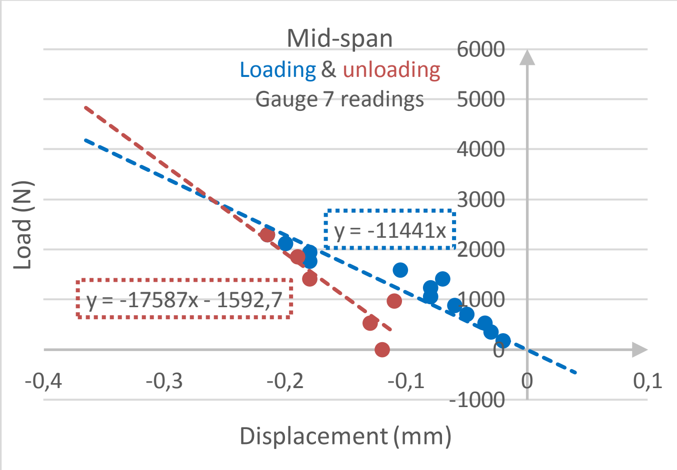


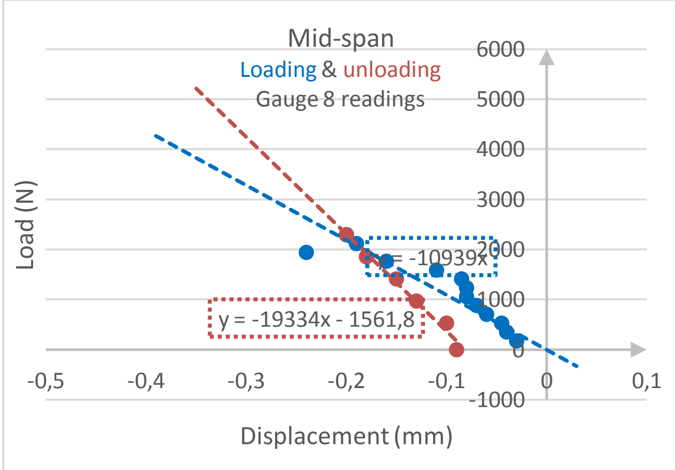












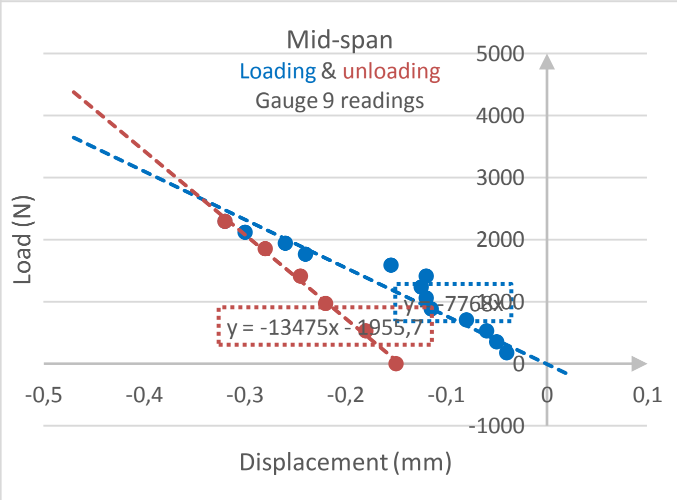


Table C2

Gauge 1		
Displacement (mm)	Point Load (kg)	Total Load (N)
-0,03	2	176,58
-0,1	4	353,16
-0,18	6	529,74
-0,25	8	706,32
-0,27	10	882,9
-0,41	12	1059,48
-0,44	14	1236,06
-0,52	16	1412,64
-0,53	18	1589,22
-0,57	20	1765,8
-0,63	22	1942,38
-0,69	24	2118,96
-0,72	26	2295,54

Gauge 2		
Displacement (mm)	Point Load (kg)	Total Load (N)
-0,05	2	176,58
-0,08	4	353,16
-0,12	6	529,74
-0,16	8	706,32
-0,16	10	882,9
-0,2	12	1059,48
-0,21	14	1236,06
-0,23	16	1412,64
-0,25	18	1589,22
-0,335	20	1765,8
-0,365	22	1942,38
-0,415	24	2118,96
-0,435	26	2295,54

-0,81	21	1854,09
	16	1412,64
-0,85	11	971,19
-0,86	6	529,74
-0,78	0	0

-0,445	21	1854,09
-0,475	16	1412,64
-0,445	11	971,19
-0,465	6	529,74
-0,395	0	0

Gauge 3		
Displacement (mm)	Point Load (kg)	Total Load (N)
-0,08	2	176,58
-0,11	4	353,16
-0,2	6	529,74
-0,33	8	706,32
-0,38	10	882,9
-0,41	12	1059,48
-0,42	14	1236,06
-0,41	16	1412,64
-0,45	18	1589,22
-0,46	20	1765,8
-0,5	22	1942,38
-0,5	24	2118,96
-0,56	26	2295,54
-0,59	21	1854,09
-0,59	16	1412,64
-0,61	11	971,19
-0,59	6	529,74
-0,55	0	0

Gauge 4		
Displacement (mm)	Point Load (kg)	Total Load (N)
-0,06	2	176,58
-0,11	4	353,16
-0,17	6	529,74
-0,24	8	706,32
-0,25	10	882,9
-0,33	12	1059,48
-0,36	14	1236,06
-0,4	16	1412,64
-0,48	18	1589,22
-0,59	20	1765,8
-0,68	22	1942,38
-0,74	24	2118,96
-0,82	26	2295,54
-0,75	21	1854,09
-0,58	16	1412,64
-0,55	11	971,19
-0,43	6	529,74
-0,31	0	0

Gauge 5		
Displacement (mm)	Point Load (kg)	Total Load (N)
-0,12	2	176,58
-0,14	4	353,16
-0,19	6	529,74
-0,23	8	706,32
-0,245	10	882,9
-0,28	12	1059,48
-0,31	14	1236,06
-0,35	16	1412,64
-0,35	18	1589,22
-0,4	20	1765,8
-0,45	22	1942,38
-0,53	24	2118,96
-0,55	26	2295,54
-0,49	21	1854,09

Gauge 6		
Displacement (mm)	Point Load (kg)	Total Load (N)
-0,12	2	176,58
-0,15	4	353,16
-0,2	6	529,74
-0,23	8	706,32
-0,31	10	882,9
-0,31	12	1059,48
-0,335	14	1236,06
-0,365	16	1412,64
-0,41	18	1589,22
-0,5	20	1765,8
-0,54	22	1942,38
-0,62	24	2118,96
-0,67	26	2295,54
-0,59	21	1854,09

-0,42	16	1412,64
-0,33	11	971,19
-0,24	6	529,74
-0,12	0	0

-0,52	16	1412,64
-0,445	11	971,19
-0,33	6	529,74
-0,22	0	0

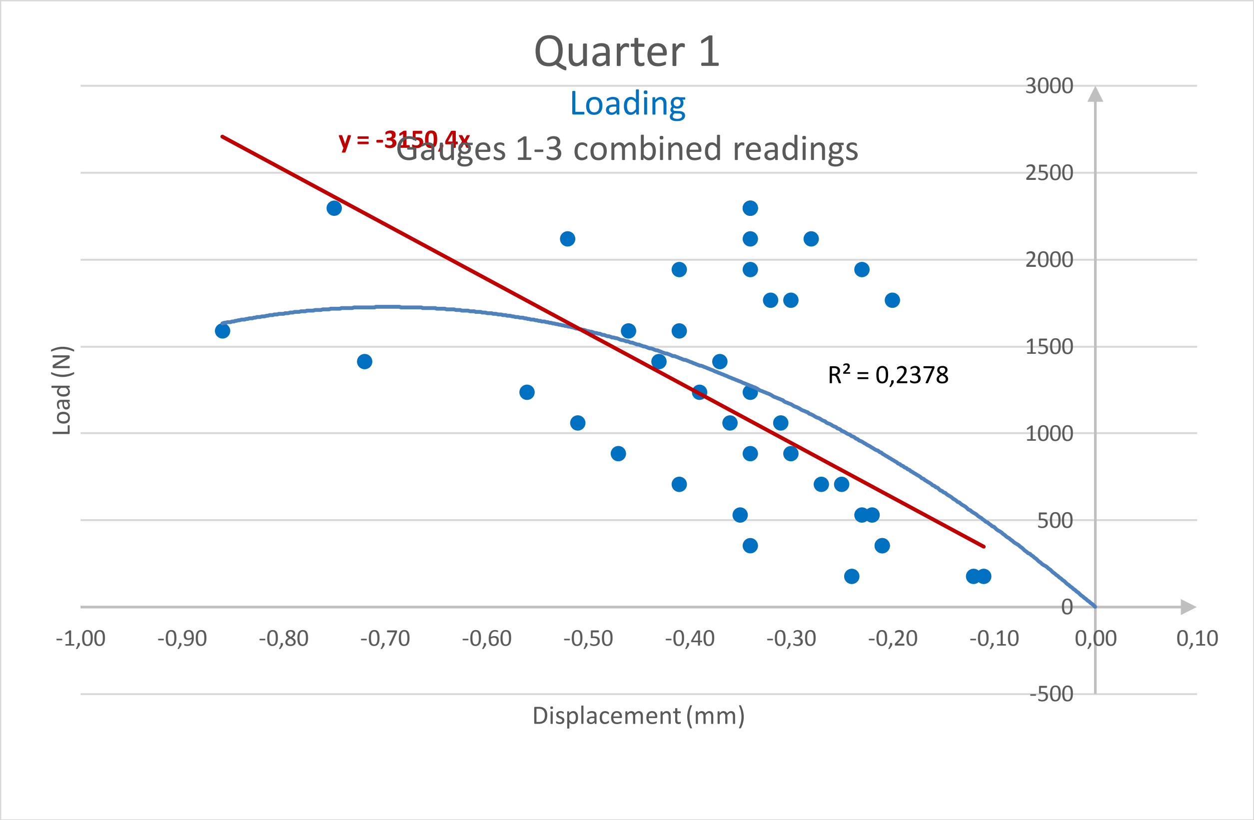
Gauge 7		
Displacement (mm)	Point Load (kg)	Total Load (N)
-0,02	2	176,58
-0,03	4	353,16
-0,035	6	529,74
-0,05	8	706,32
-0,06	10	882,9
-0,08	12	1059,48
-0,08	14	1236,06
-0,07	16	1412,64
-0,105	18	1589,22
-0,18	20	1765,8
-0,18	22	1942,38
-0,2	24	2118,96
-0,215	26	2295,54
-0,19	21	1854,09
-0,18	16	1412,64
-0,11	11	971,19
-0,13	6	529,74
-0,12	0	0

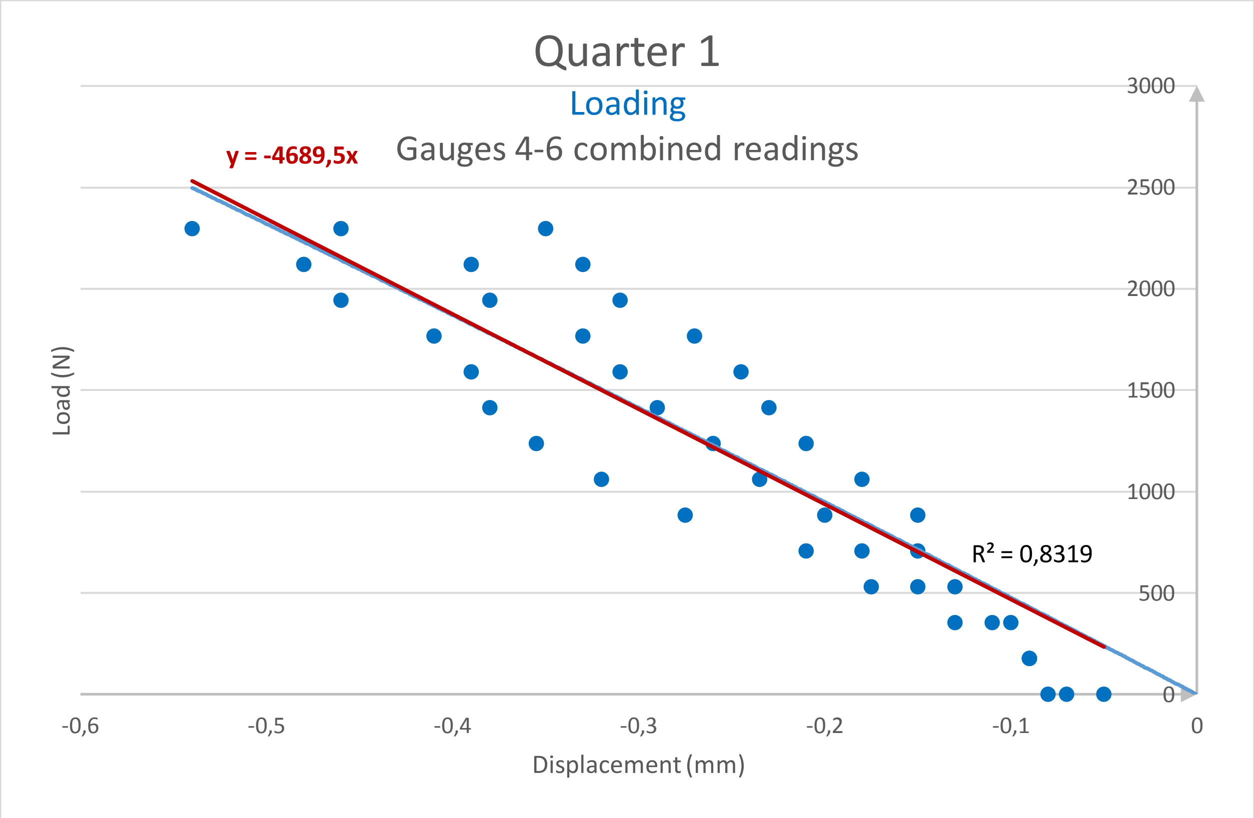
Gauge 8		
Displacement (mm)	Point Load (kg)	Total Load (N)
-0,03	2	176,58
-0,04	4	353,16
-0,045	6	529,74
-0,06	8	706,32
-0,07	10	882,9
-0,08	12	1059,48
-0,08	14	1236,06
-0,085	16	1412,64
-0,11	18	1589,22
-0,16	20	1765,8
-0,24	22	1942,38
-0,19	24	2118,96
-0,2	26	2295,54
-0,18	21	1854,09
-0,15	16	1412,64
-0,13	11	971,19
-0,1	6	529,74
-0,09	0	0

Gauge 9		
Displacement (mm)	Point Load (kg)	Total Load (N)
-0,04	2	176,58
-0,05	4	353,16
-0,06	6	529,74
-0,08	8	706,32
-0,115	10	882,9
-0,12	12	1059,48
-0,125	14	1236,06
-0,12	16	1412,64
-0,155	18	1589,22
-0,24	20	1765,8
-0,26	22	1942,38
-0,3	24	2118,96
-0,32	26	2295,54
-0,28	21	1854,09
-0,245	16	1412,64

-0,22	11	971,19
-0,18	6	529,74
-0,15	0	0

Quarter 1 loading





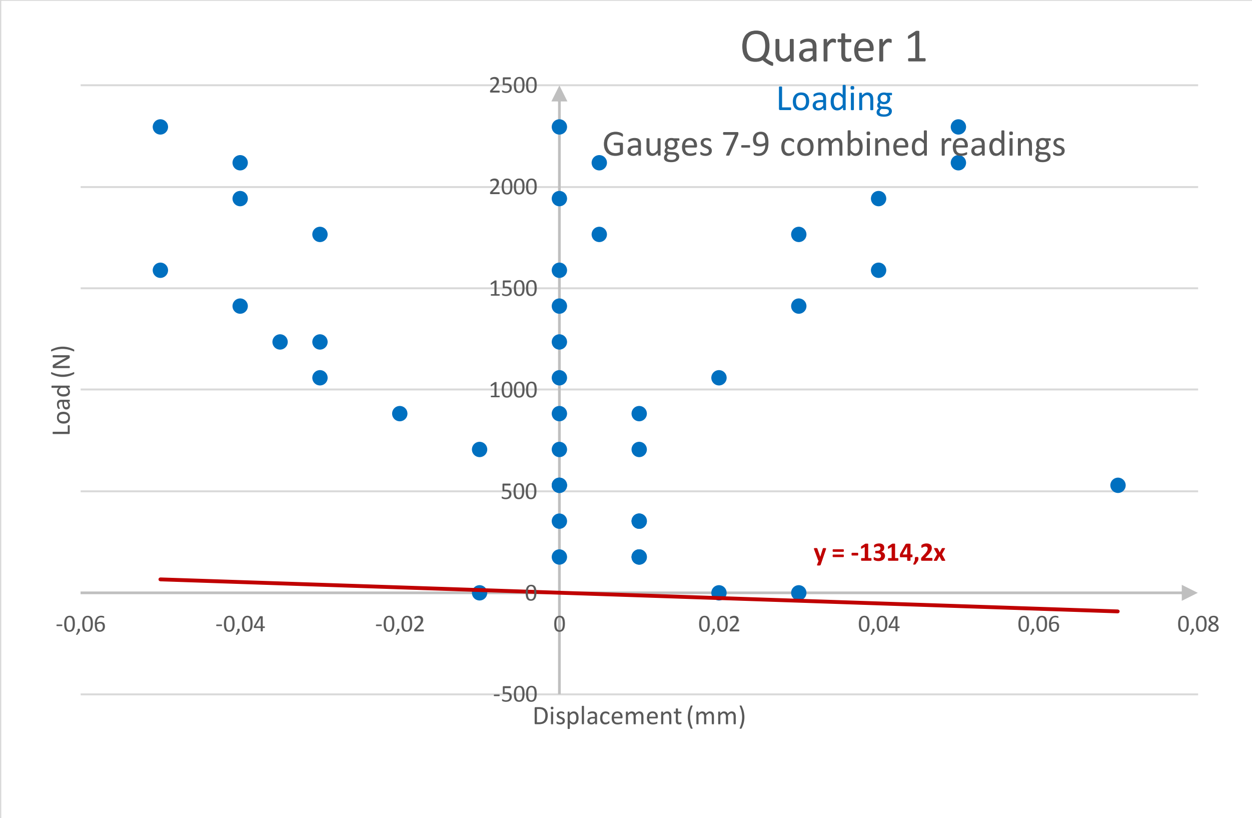
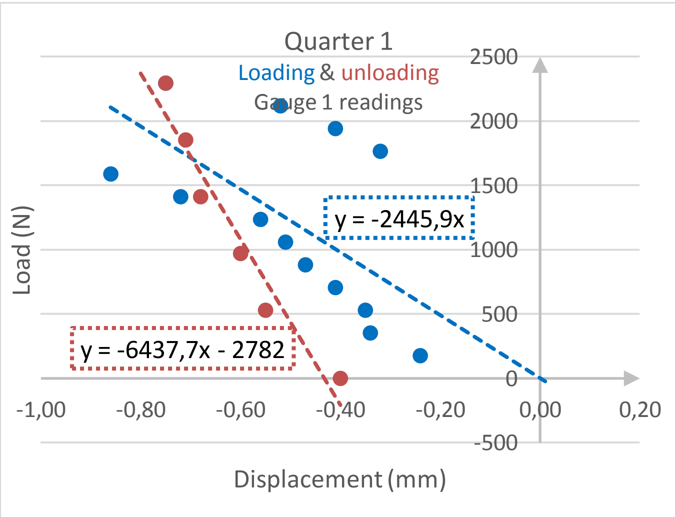
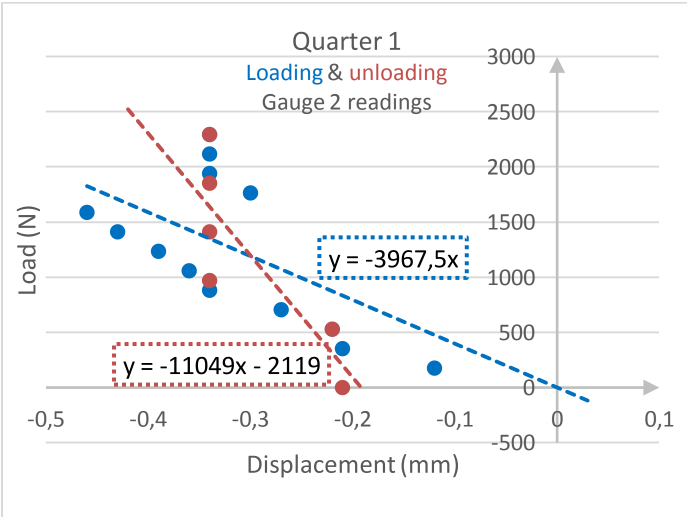
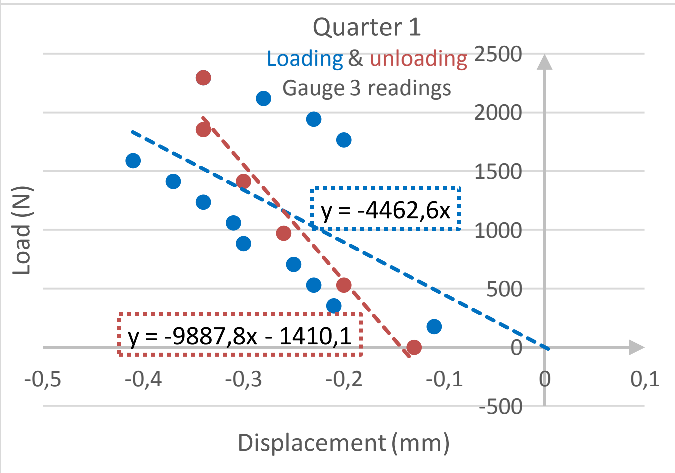
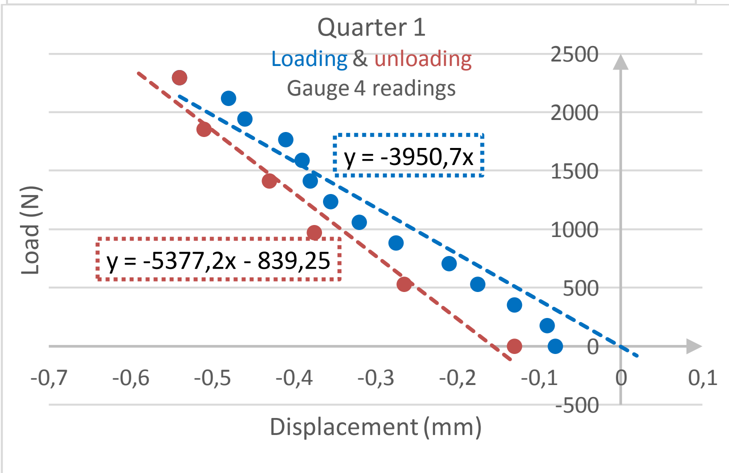

Quarter 1
Loading
Gauges 7-9 combined readings
y = -1314,2x
Load (N)
Displacement (mm)

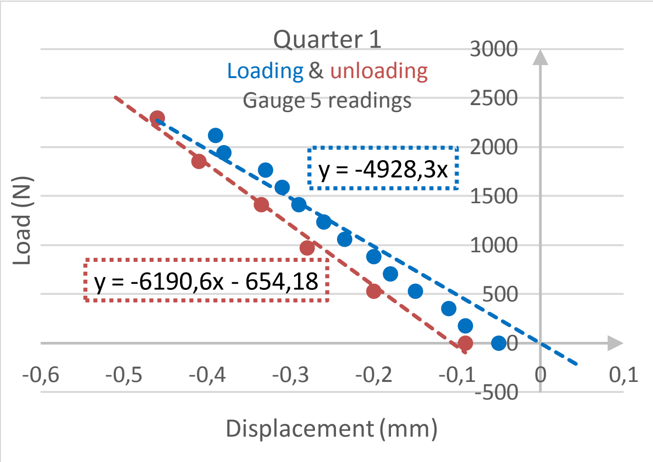
Table C3

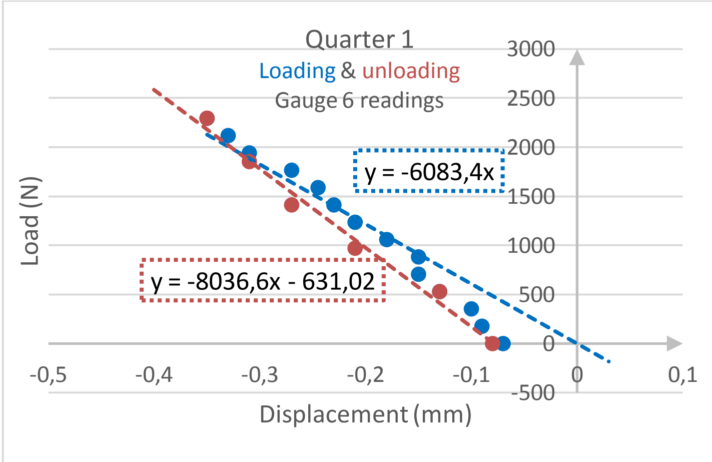

Quarter 1
Loading & unloading
Gauge 1 readings
y = -2445,9x
y = -6437,7x - 2782
Load (N)
Displacement (mm)

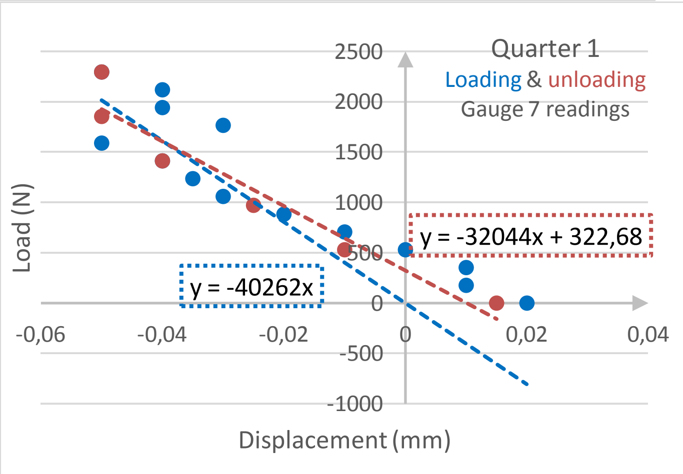

Quarter 1
Loading & unloading
Gauge 2 readings
y = -3967,5x
y = -11049x - 2119
Load (N)
Displacement (mm)

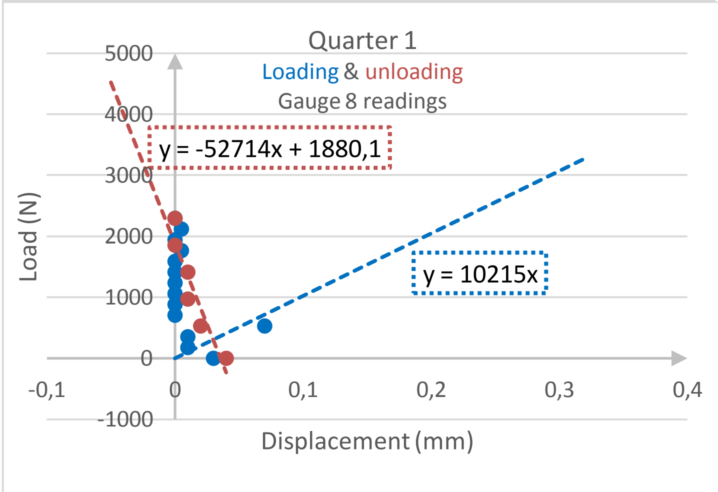

Quarter 1
Loading & unloading
Gauge 3 readings
y = -4462,6x
y = -9887,8x - 1410,1
Load (N)
Displacement (mm)


Quarter 1
Loading & unloading
Gauge 4 readings
y = -3950,7x
y = -5377,2x - 839,25
Load (N)
Displacement (mm)









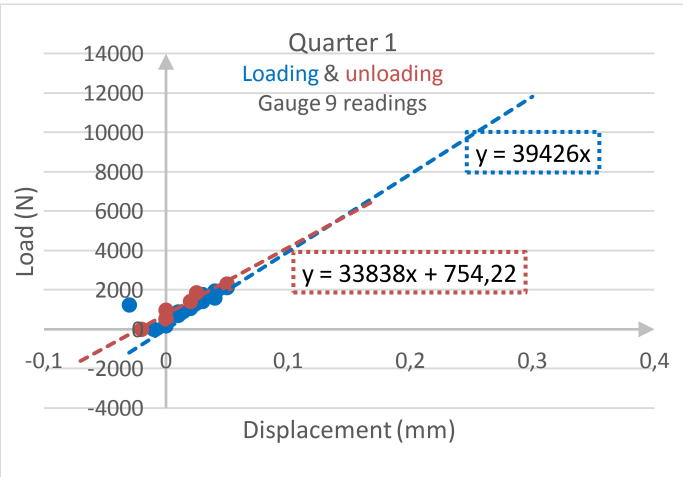


Table C4

Gauge 1		
Displacement (mm)	Point Load (kg)	Total Load (N)
-0,24	2	176,58
-0,34	4	353,16
-0,35	6	529,74

Gauge 2		
Displacement (mm)	Point Load (kg)	Total Load (N)
-0,12	2	176,58
-0,21	4	353,16
-0,22	6	529,74

-0,41	8	706,32
-0,47	10	882,9
-0,51	12	1059,48
-0,56	14	1236,06
-0,72	16	1412,64
-0,86	18	1589,22
-0,32	20	1765,8
-0,41	22	1942,38
-0,52	24	2118,96
-0,75	26	2295,54
-0,71	21	1854,09
-0,68	16	1412,64
-0,60	11	971,19
-0,55	6	529,74
-0,40	0	0

-0,27	8	706,32
-0,34	10	882,9
-0,36	12	1059,48
-0,39	14	1236,06
-0,43	16	1412,64
-0,46	18	1589,22
-0,3	20	1765,8
-0,34	22	1942,38
-0,34	24	2118,96
-0,34	26	2295,54
-0,34	21	1854,09
-0,34	16	1412,64
-0,34	11	971,19
-0,22	6	529,74
-0,21	0	0

Gauge 3		
Displacement (mm)	**Point Load (kg)**	**Total Load (N)**
-0,11	2	176,58
-0,21	4	353,16
-0,23	6	529,74
-0,25	8	706,32
-0,3	10	882,9
-0,31	12	1059,48
-0,34	14	1236,06
-0,37	16	1412,64
-0,41	18	1589,22
-0,2	20	1765,8
-0,23	22	1942,38
-0,28	24	2118,96
-0,34	26	2295,54
-0,34	21	1854,09
-0,3	16	1412,64
-0,26	11	971,19
-0,2	6	529,74
-0,13	0	0

Gauge 4		
Displacement (mm)	**Point Load (kg)**	**Total Load (N)**
-0,09	2	176,58
-0,13	4	353,16
-0,175	6	529,74
-0,21	8	706,32
-0,275	10	882,9
-0,32	12	1059,48
-0,355	14	1236,06
-0,38	16	1412,64
-0,39	18	1589,22
-0,08	0	0
-0,41	20	1765,8
-0,46	22	1942,38
-0,48	24	2118,96
-0,54	26	2295,54
-0,51	21	1854,09
-0,43	16	1412,64
-0,375	11	971,19
-0,265	6	529,74

Gauge 5		
Displacement (mm)	**Point Load (kg)**	**Total Load (N)**
-0,09	2	176,58
-0,11	4	353,16
-0,15	6	529,74
-0,18	8	706,32
-0,2	10	882,9

Gauge 6		
Displacement (mm)	**Point Load (kg)**	**Total Load (N)**
-0,09	2	176,58
-0,1	4	353,16
-0,13	6	529,74
-0,15	8	706,32
-0,15	10	882,9

-0,235	12	1059,48
-0,26	14	1236,06
-0,29	16	1412,64
-0,31	18	1589,22
-0,05	0	0
-0,33	20	1765,8
-0,38	22	1942,38
-0,39	24	2118,96
-0,46	26	2295,54
-0,41	21	1854,09
-0,335	16	1412,64
-0,28	11	971,19
-0,2	6	529,74
-0,09	0	0

-0,18	12	1059,48
-0,21	14	1236,06
-0,23	16	1412,64
-0,245	18	1589,22
-0,07	0	0
-0,27	20	1765,8
-0,31	22	1942,38
-0,33	24	2118,96
-0,35	26	2295,54
-0,31	21	1854,09
-0,27	16	1412,64
-0,21	11	971,19
-0,13	6	529,74
-0,08	0	0

Gauge 7		
Displacement (mm)	**Point Load (kg)**	**Total Load (N)**
0,01	2	176,58
0,01	4	353,16
0	6	529,74
-0,01	8	706,32
-0,02	10	882,9
-0,03	12	1059,48
-0,035	14	1236,06
-0,04	16	1412,64
-0,05	18	1589,22
0,02	0	0
-0,03	20	1765,8
-0,04	22	1942,38
-0,04	24	2118,96
-0,05	26	2295,54
-0,05	21	1854,09
-0,04	16	1412,64
-0,025	11	971,19
-0,01	6	529,74
0,015	0	0

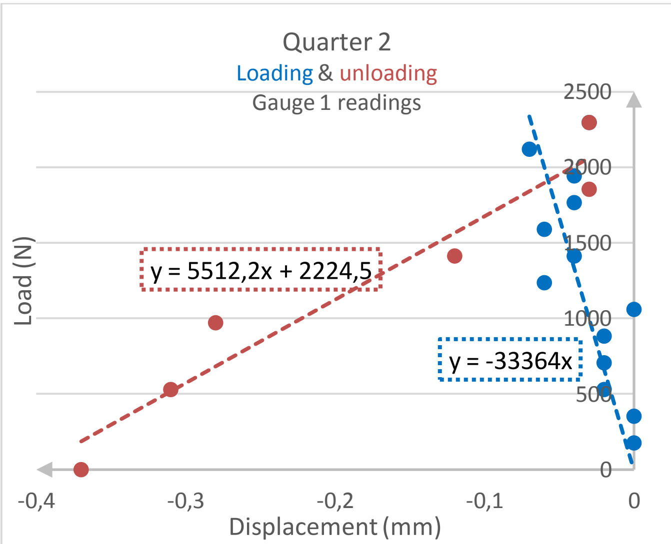
Gauge 8		
Displacement (mm)	**Point Load (kg)**	**Total Load (N)**
0,01	2	176,58
0,01	4	353,16
0,07	6	529,74
0	8	706,32
0	10	882,9
0	12	1059,48
0	14	1236,06
0	16	1412,64
0	18	1589,22
0,03	0	0
0,005	20	1765,8
0	22	1942,38
0,005	24	2118,96
0	26	2295,54
0	21	1854,09
0,01	16	1412,64
0,01	11	971,19
0,02	6	529,74
0,04	0	0

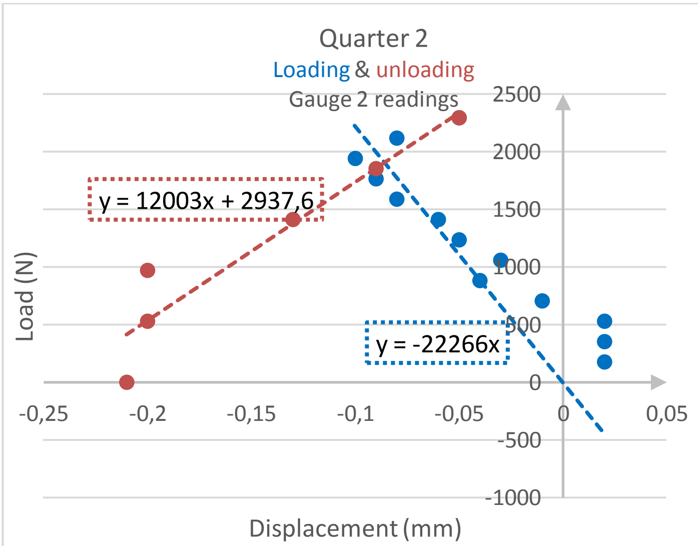
Gauge 9		
Displacement (mm)	**Point Load (kg)**	**Total Load (N)**
0	2	176,58
0	4	353,16
0	6	529,74
0,01	8	706,32
0,01	10	882,9

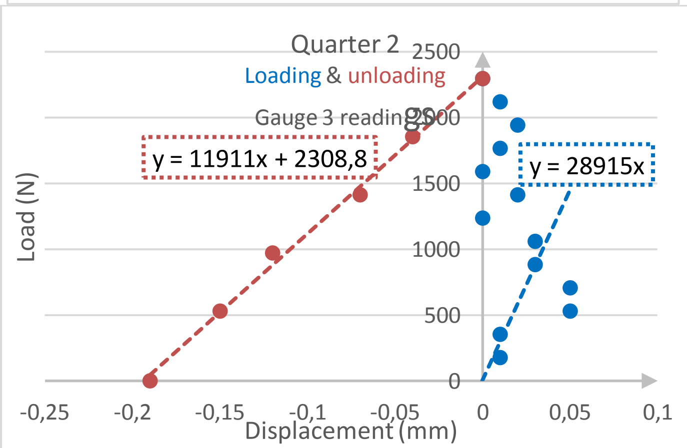
0,02	12	1059,48
-0,03	14	1236,06
0,03	16	1412,64
0,04	18	1589,22
-0,01	0	0
0,03	20	1765,8
0,04	22	1942,38
0,05	24	2118,96
0,05	26	2295,54
0,025	21	1854,09
0,02	16	1412,64
0	11	971,19
0	6	529,74
-0,02	0	0

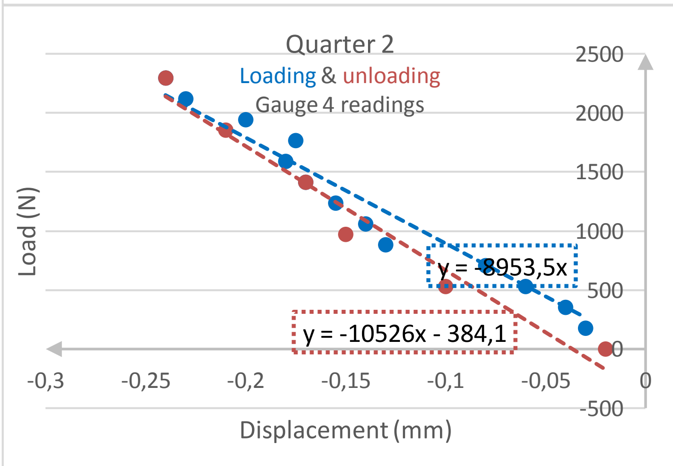
QUARTER 2 LOADING

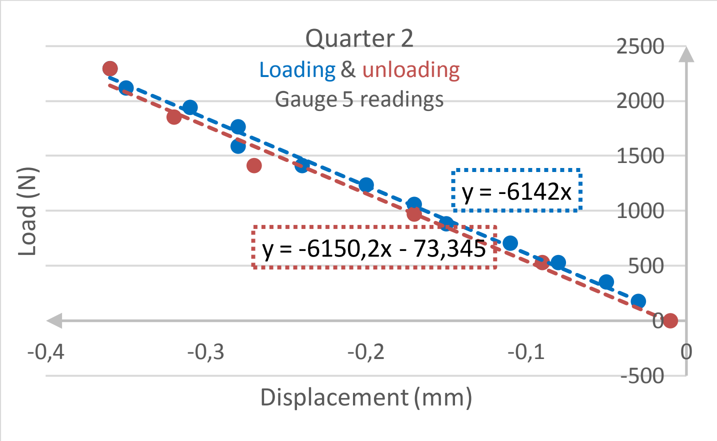
Table C5

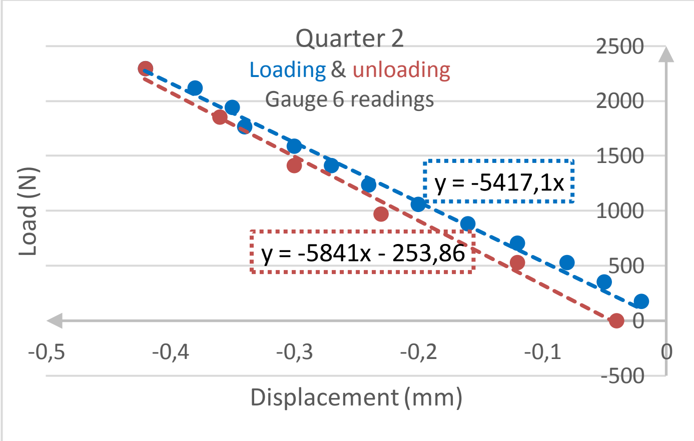


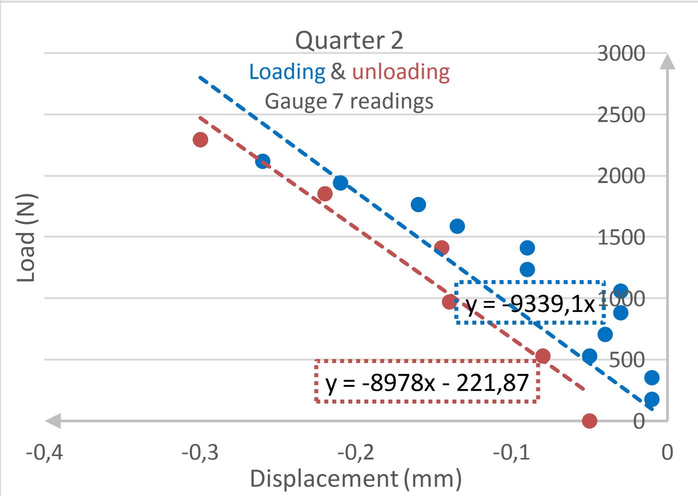


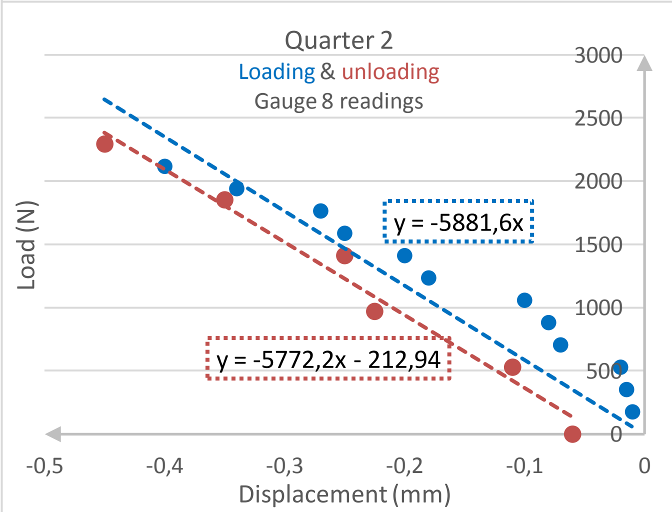


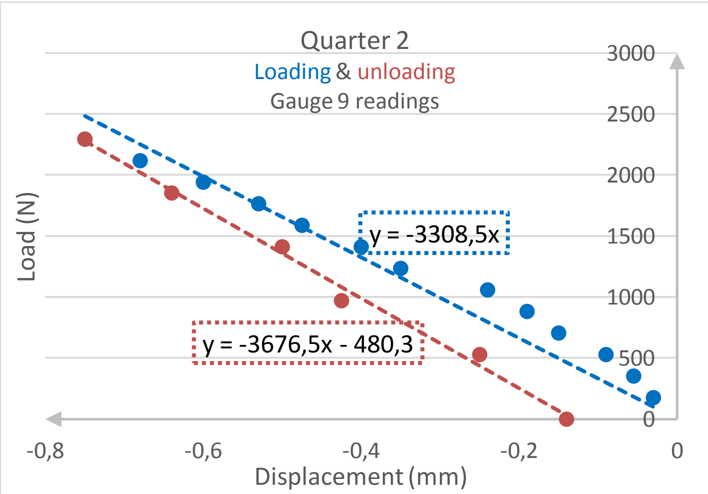


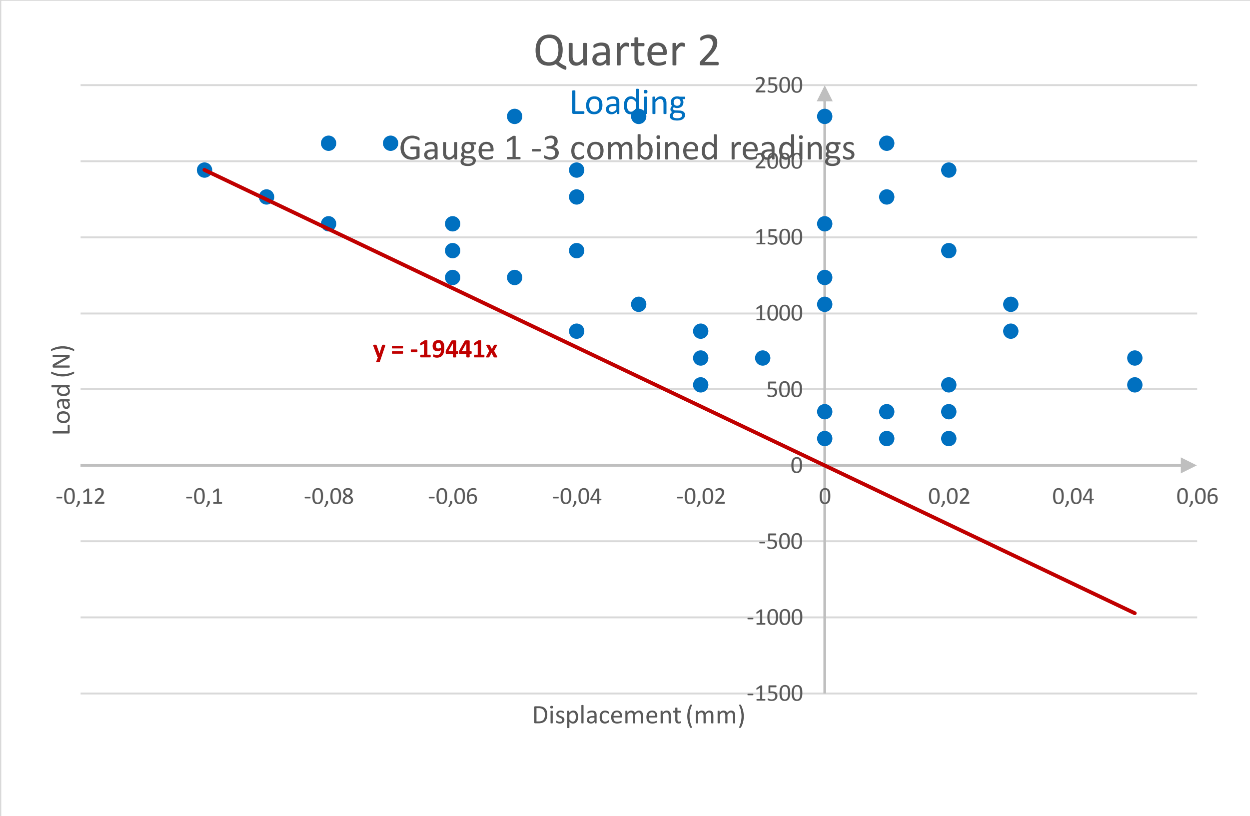

Quarter 2
Loading & unloading
Gauge 5 readings
y = -6142x
y = -6150,2x - 73,345
Load (N)
Displacement (mm)
2500
2000
1500
1000
500
0
-500
-0,4
-0,3
-0,2
-0,1
0

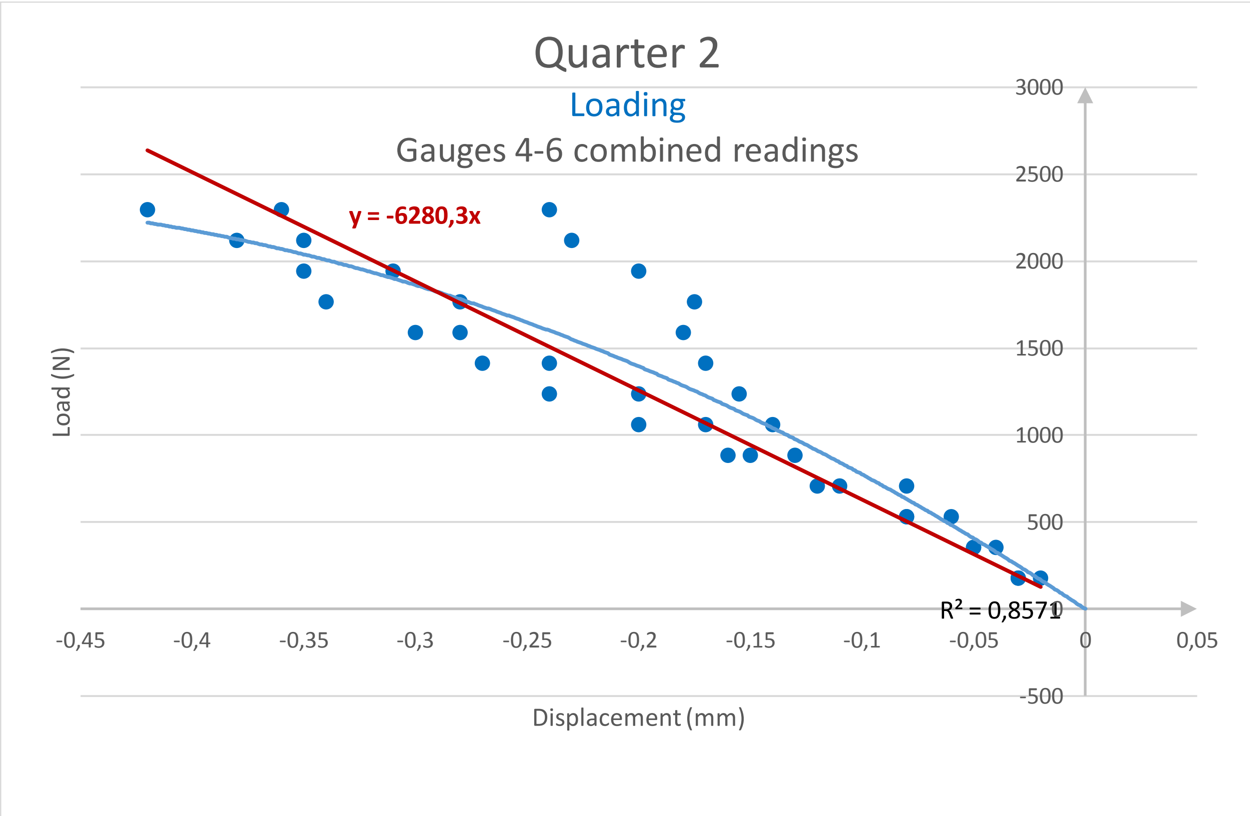

Quarter 2
Loading & unloading
Gauge 6 readings
y = -5417,1x
y = -5841x - 253,86
Load (N)
Displacement (mm)
2500
2000
1500
1000
500
0
-500
-0,5
-0,4
-0,3
-0,2
-0,1
0


Quarter 2
Loading & unloading
Gauge 7 readings
y = -9339,1x
y = -8978x - 221,87
Load (N)
Displacement (mm)
3000
2500
2000
1500
1000
500
0
-0,4
-0,3
-0,2
-0,1
0


Quarter 2
Loading & unloading
Gauge 8 readings
y = -5881,6x
y = -5772,2x - 212,94
Load (N)
Displacement (mm)
3000
2500
2000
1500
1000
500
0
-0,5
-0,4
-0,3
-0,2
-0,1
0


Quarter 2
Loading & unloading
Gauge 9 readings
y = -3308,5x
y = -3676,5x - 480,3
Load (N)
Displacement (mm)
3000
2500
2000
1500
1000
500
0
-0,8
-0,6
-0,4
-0,2
0


Quarter 2
Loading
Gauge 1 -3 combined readings
y = -19441x
Load (N)
Displacement (mm)
2500
2000
1500
1000
500
0
-500
-1000
-1500
-0,12
-0,1
-0,08
-0,06
-0,04
-0,02
0
0,02
0,04
0,06


Quarter 2
Loading
Gauges 4-6 combined readings
y = -6280,3x
R² = 0,8571
Load (N)
Displacement (mm)
3000
2500
2000
1500
1000
500
0
-500
-0,45
-0,4
-0,35
-0,3
-0,25
-0,2
-0,15
-0,1
-0,05
0
0,05

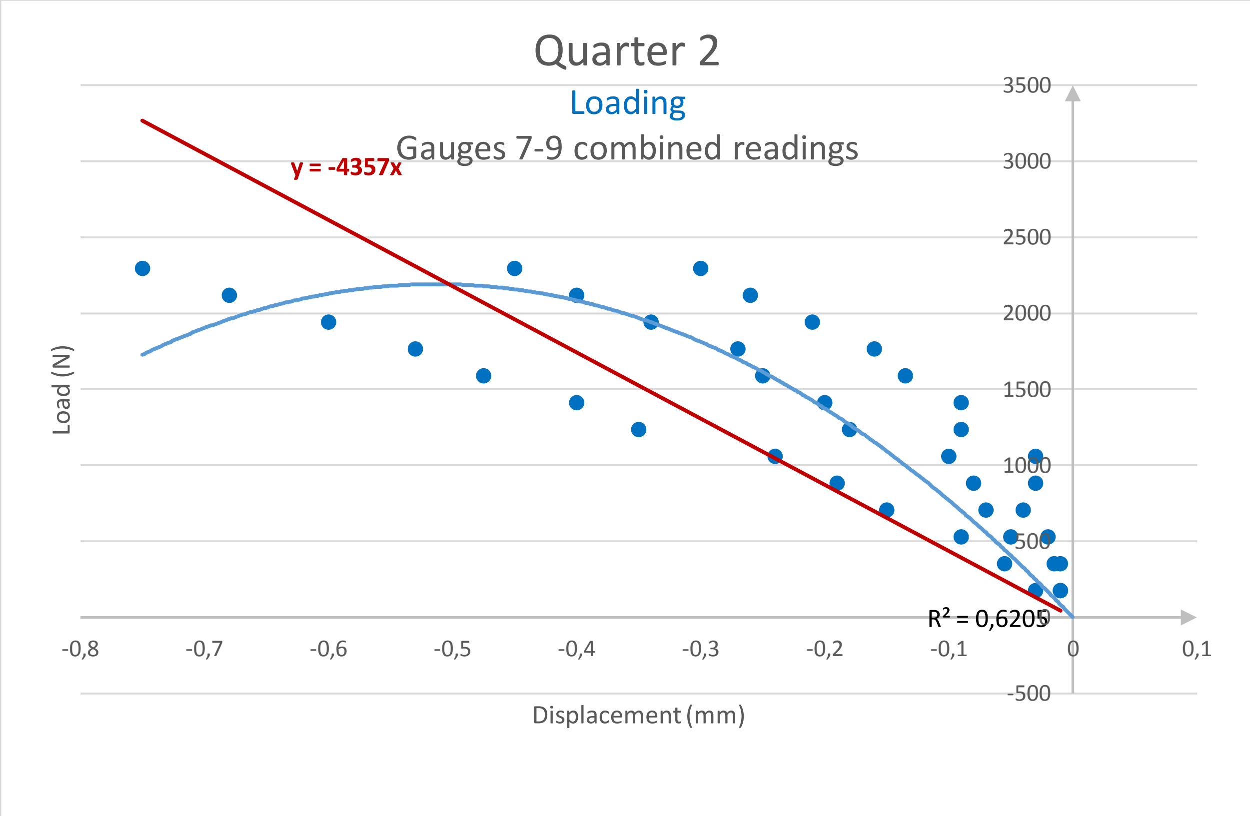


Table C6

Gauge 1		
Displacement (mm)	Point Load (kg)	Load (N)
0	2	176,58
0	4	353,16
-0,02	6	529,74
-0,02	8	706,32
-0,02	10	882,9
0	12	1059,48
-0,06	14	1236,06
-0,04	16	1412,64
-0,06	18	1589,22
-0,04	20	1765,8
-0,04	22	1942,38
-0,07	24	2118,96
-0,03	26	2295,54
-0,03	21	1854,09
-0,12	16	1412,64
-0,28	11	971,19
-0,31	6	529,74
-0,37	0	0

Gauge 2		
Displacement (mm)	Point Load (kg)	Total Load (N)
0,02	2	176,58
0,02	4	353,16
0,02	6	529,74
-0,01	8	706,32
-0,04	10	882,9
-0,03	12	1059,48
-0,05	14	1236,06
-0,06	16	1412,64
-0,08	18	1589,22
-0,09	20	1765,8
-0,1	22	1942,38
-0,08	24	2118,96
-0,05	26	2295,54
-0,09	21	1854,09
-0,13	16	1412,64
-0,2	11	971,19
-0,2	6	529,74
-0,21	0	0

Gauge 3		
Displacement (mm)	Point Load	Total Load

Gauge 4		
Displacement (mm)	Point Load	Total Load

	(kg)	(N)
0,01	2	176,58
0,01	4	353,16
0,05	6	529,74
0,05	8	706,32
0,03	10	882,9
0,03	12	1059,48
0	14	1236,06
0,02	16	1412,64
0	18	1589,22
0,01	20	1765,8
0,02	22	1942,38
0,01	24	2118,96
0	26	2295,54
-0,04	21	1854,09
-0,07	16	1412,64
-0,12	11	971,19
-0,15	6	529,74
-0,19	0	0

	(kg)	(N)
-0,03	2	176,58
-0,04	4	353,16
-0,06	6	529,74
-0,08	8	706,32
-0,13	10	882,9
-0,14	12	1059,48
-0,155	14	1236,06
-0,17	16	1412,64
-0,18	18	1589,22
-0,175	20	1765,8
-0,2	22	1942,38
-0,23	24	2118,96
-0,24	26	2295,54
-0,21	21	1854,09
-0,17	16	1412,64
-0,15	11	971,19
-0,1	6	529,74
-0,02	0	0

Gauge 5		
Displacement (mm)	Point Load (kg)	Total Load (N)
-0,03	2	176,58
-0,05	4	353,16
-0,08	6	529,74
-0,11	8	706,32
-0,15	10	882,9
-0,17	12	1059,48
-0,2	14	1236,06
-0,24	16	1412,64
-0,28	18	1589,22
-0,28	20	1765,8
-0,31	22	1942,38
-0,35	24	2118,96
-0,36	26	2295,54
-0,32	21	1854,09
-0,27	16	1412,64
-0,17	11	971,19
-0,09	6	529,74
-0,01	0	0

Gauge 6		
Displacement (mm)	Point Load (kg)	Total Load (N)
-0,02	2	176,58
-0,05	4	353,16
-0,08	6	529,74
-0,12	8	706,32
-0,16	10	882,9
-0,2	12	1059,48
-0,24	14	1236,06
-0,27	16	1412,64
-0,3	18	1589,22
-0,34	20	1765,8
-0,35	22	1942,38
-0,38	24	2118,96
-0,42	26	2295,54
-0,36	21	1854,09
-0,3	16	1412,64
-0,23	11	971,19
-0,12	6	529,74
-0,04	0	0

Gauge 7		
Displacement (mm)	Point Load (kg)	Total Load (N)
-0,01	2	176,58

Gauge 8		
Displacement (mm)	Point Load (kg)	Total Load (N)
-0,01	2	176,58

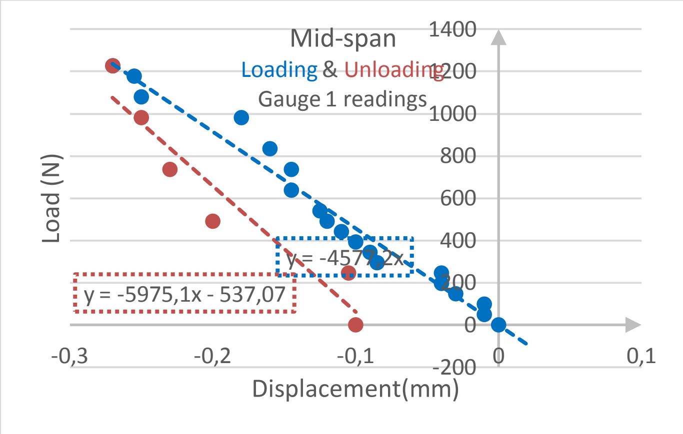
-0,01	4	353,16	-0,015	4	353,16
-0,05	6	529,74	-0,02	6	529,74
-0,04	8	706,32	-0,07	8	706,32
-0,03	10	882,9	-0,08	10	882,9
-0,03	12	1059,48	-0,1	12	1059,48
-0,09	14	1236,06	-0,18	14	1236,06
-0,09	16	1412,64	-0,2	16	1412,64
-0,135	18	1589,22	-0,25	18	1589,22
-0,16	20	1765,8	-0,27	20	1765,8
-0,21	22	1942,38	-0,34	22	1942,38
-0,26	24	2118,96	-0,4	24	2118,96
-0,3	26	2295,54	-0,45	26	2295,54
-0,22	21	1854,09	-0,35	21	1854,09
-0,145	16	1412,64	-0,25	16	1412,64
-0,14	11	971,19	-0,225	11	971,19
-0,08	6	529,74	-0,11	6	529,74
-0,05	0	0	-0,06	0	0

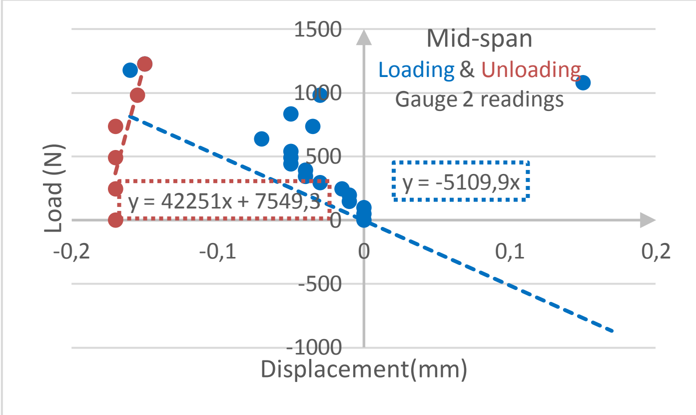
Gauge 9		
Displacement (mm)	**Point Load (kg)**	**Total Load (N)**
-0,03	2	176,58
-0,055	4	353,16
-0,09	6	529,74
-0,15	8	706,32
-0,19	10	882,9
-0,24	12	1059,48
-0,35	14	1236,06
-0,4	16	1412,64
-0,475	18	1589,22
-0,53	20	1765,8
-0,6	22	1942,38
-0,68	24	2118,96
-0,75	26	2295,54
-0,64	21	1854,09
-0,5	16	1412,64
-0,425	11	971,19
-0,25	6	529,74
-0,14	0	0

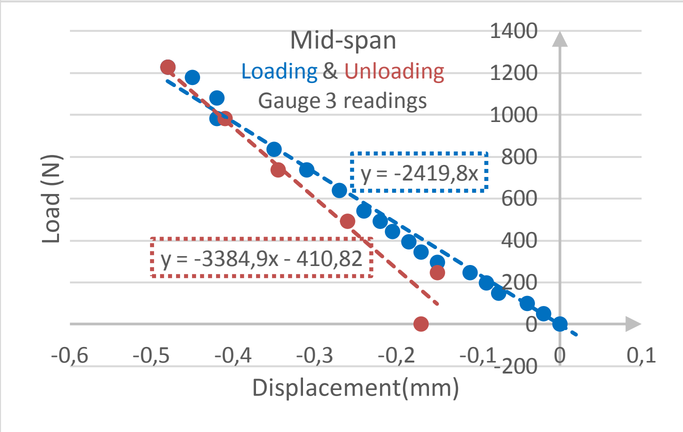
SHELL 2

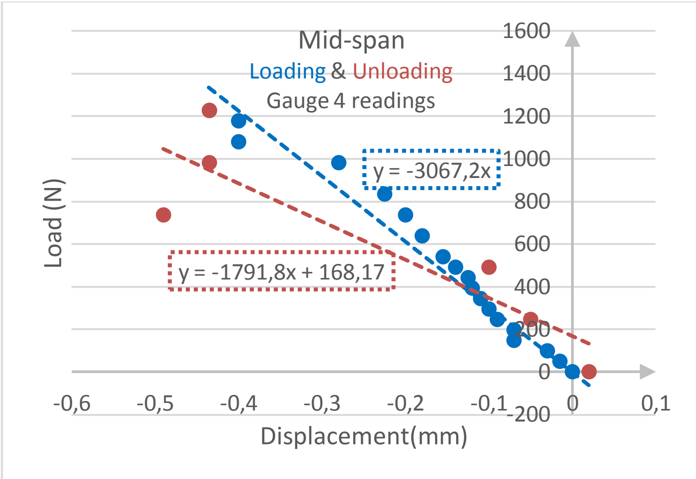
MIDSPAN LOADING

Table C7









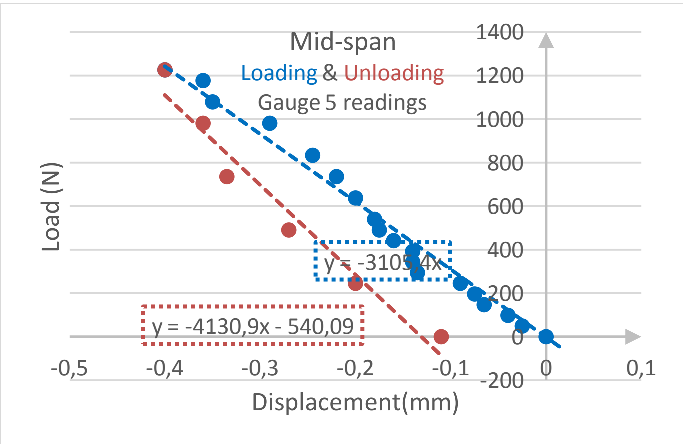


Table C8

Gauge 1		
Displacement (mm)	Point Load (kg)	Total Load (N)
0	0	0
-0,01	1	49,05
-0,01	2	98,1
-0,03	3	147,15
-0,04	4	196,2

Gauge 2		
Displacement (mm)	Point Load (kg)	Total Load (N)
0	0	0
0	1	49,05
0	2	98,1
-0,01	3	147,15
-0,01	4	196,2

-0,04	5	245,25	-0,015	5	245,25
-0,085	6	294,3	-0,03	6	294,3
-0,09	7	343,35	-0,04	7	343,35
-0,1	8	392,4	-0,04	8	392,4
-0,11	9	441,45	-0,05	9	441,45
-0,12	10	490,5	-0,05	10	490,5
-0,125	11	539,55	-0,05	11	539,55
-0,145	13	637,65	-0,07	13	637,65
-0,145	15	735,75	-0,035	15	735,75
-0,16	17	833,85	-0,05	17	833,85
-0,18	20	981	-0,03	20	981
-0,25	22	1079,1	0,15	22	1079,1
-0,255	24	1177,2	-0,16	24	1177,2
-0,27	25	1226,25	-0,15	25	1226,25
-0,25	20	981	-0,155	20	981
-0,23	15	735,75	-0,17	15	735,75
-0,2	10	490,5	-0,17	10	490,5
-0,105	5	245,25	-0,17	5	245,25
-0,1	0	0	-0,17	0	0

Gauge 3		
Displacement (mm)	Point Load (kg)	Total Load (N)
0	0	0
-0,02	1	49,05
-0,04	2	98,1
-0,075	3	147,15
-0,09	4	196,2
-0,11	5	245,25
-0,15	6	294,3
-0,17	7	343,35
-0,185	8	392,4
-0,205	9	441,45
-0,22	10	490,5
-0,24	11	539,55
-0,27	13	637,65
-0,31	15	735,75
-0,35	17	833,85
-0,42	20	981
-0,42	22	1079,1
-0,45	24	1177,2
-0,48	25	1226,25
-0,41	20	981
-0,345	15	735,75
-0,26	10	490,5
-0,15	5	245,25
-0,17	0	0

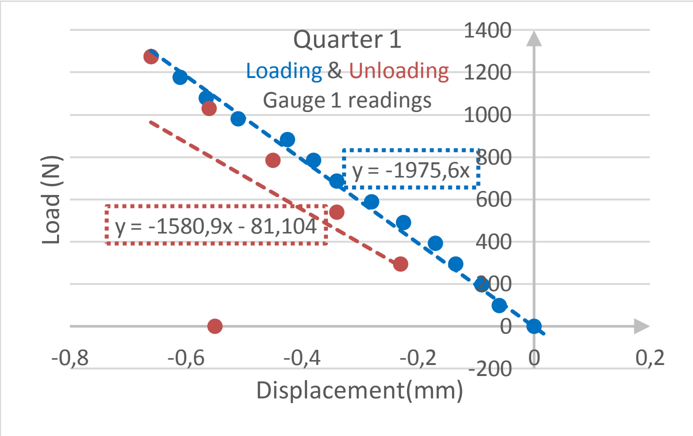
Gauge 4		
Displacement (mm)	Point Load (kg)	Total Load (N)
0	0	0
-0,015	1	49,05
-0,03	2	98,1
-0,07	3	147,15
-0,07	4	196,2
-0,09	5	245,25
-0,1	6	294,3
-0,11	7	343,35
-0,12	8	392,4
-0,125	9	441,45
-0,14	10	490,5
-0,155	11	539,55
-0,18	13	637,65
-0,2	15	735,75
-0,225	17	833,85
-0,28	20	981
-0,4	22	1079,1
-0,4	24	1177,2
-0,435	25	1226,25
-0,435	20	981
-0,49	15	735,75
-0,1	10	490,5
-0,05	5	245,25
0,02	0	0

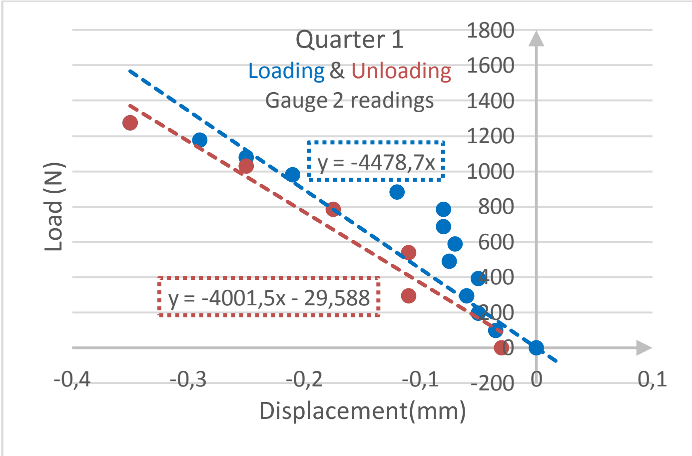
Gauge 5		
Displacement (mm)	Point Load (kg)	Total Load (N)
0	0	0
-0,025	1	49,05
-0,04	2	98,1
-0,065	3	147,15
-0,075	4	196,2
-0,09	5	245,25
-0,135	6	294,3
-0,14	7	343,35
-0,14	8	392,4
-0,16	9	441,45
-0,175	10	490,5
-0,18	11	539,55
-0,2	13	637,65
-0,22	15	735,75
-0,245	17	833,85
-0,29	20	981
-0,35	22	1079,1
-0,36	24	1177,2
-0,4	25	1226,25
-0,36	20	981
-0,335	15	735,75
-0,27	10	490,5
-0,2	5	245,25
-0,11	0	0

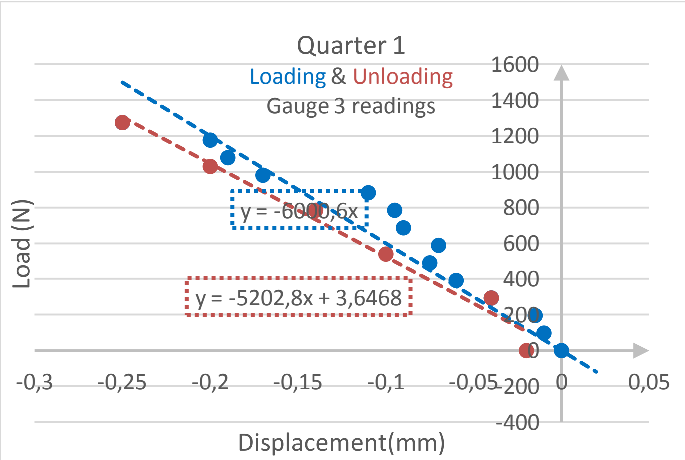
Gauge 6		
Displacement (mm)	Point Load (kg)	Total Load (N)
0	0	0
-0,02	1	49,05
-0,02	2	98,1
-0,02	3	147,15
-0,04	4	196,2
-0,04	5	245,25
0	6	294,3
-0,01	7	343,35
0	8	392,4
0	9	441,45
-	10	490,5
-	11	539,55
-	13	637,65
-	15	735,75
-	17	833,85
-	20	981
0,03	22	1079,1
0,02	24	1177,2
-	25	1226,25
-	20	981
-	15	735,75
-	10	490,5
-	5	245,25
-	0	0

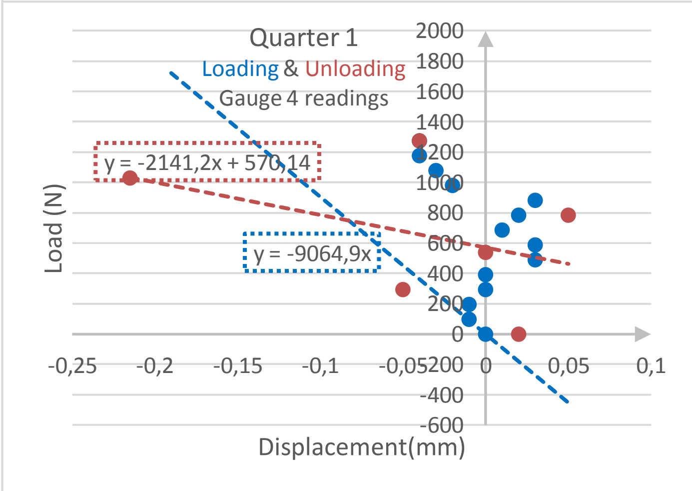
Quarter 1 loading

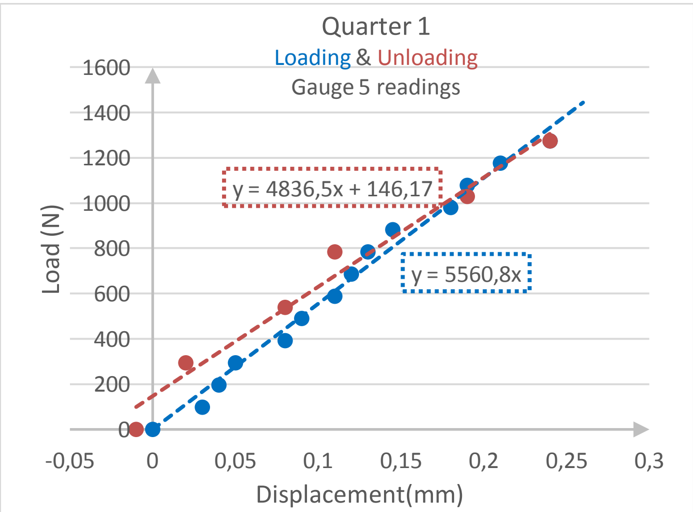
Table C9

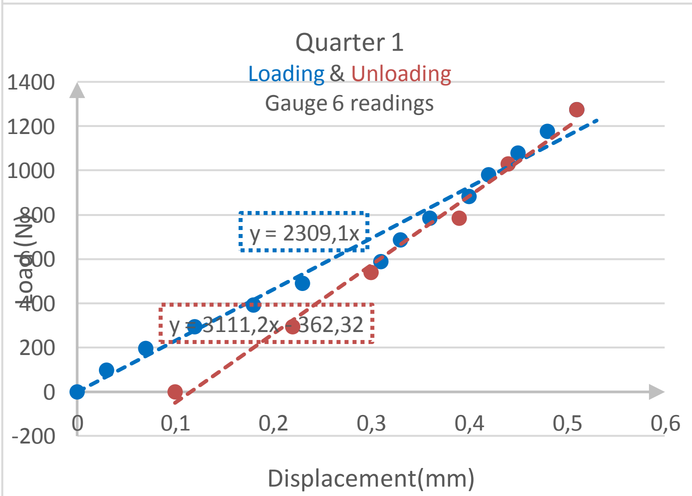


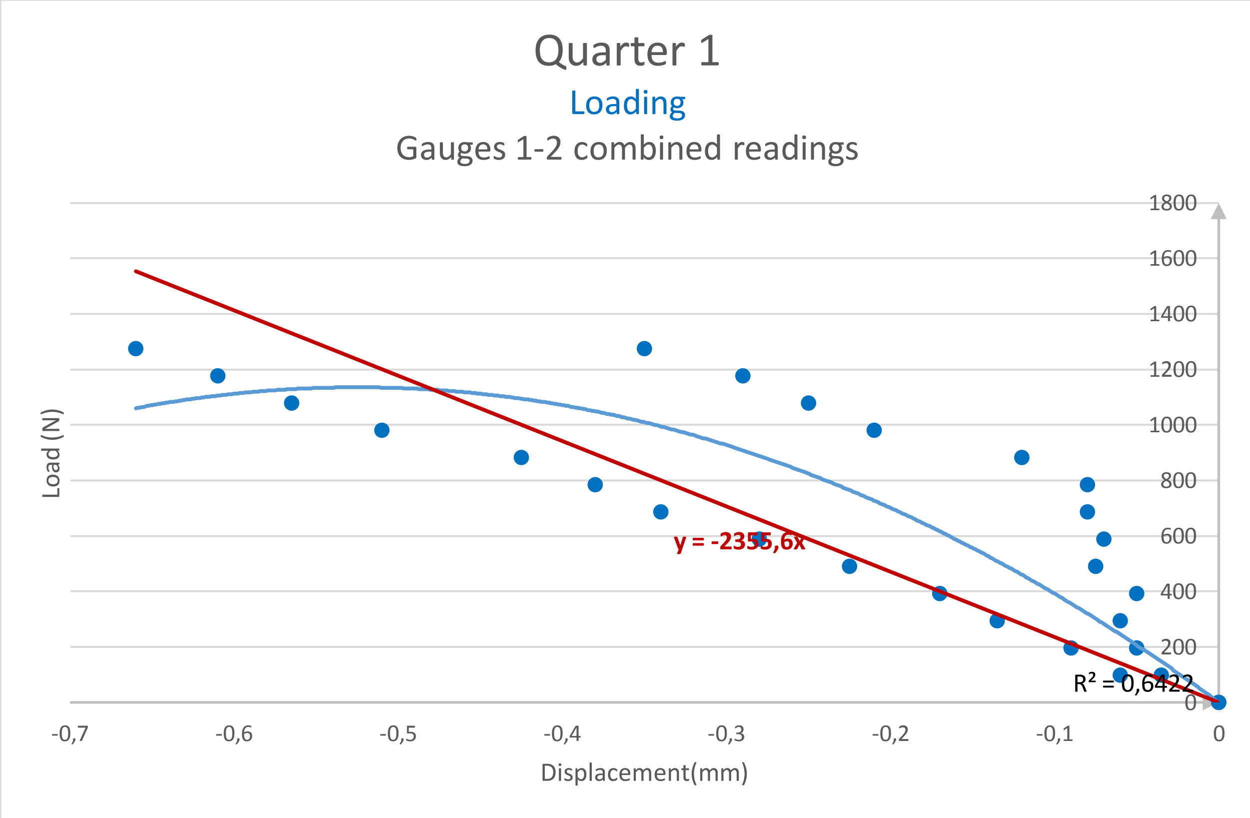


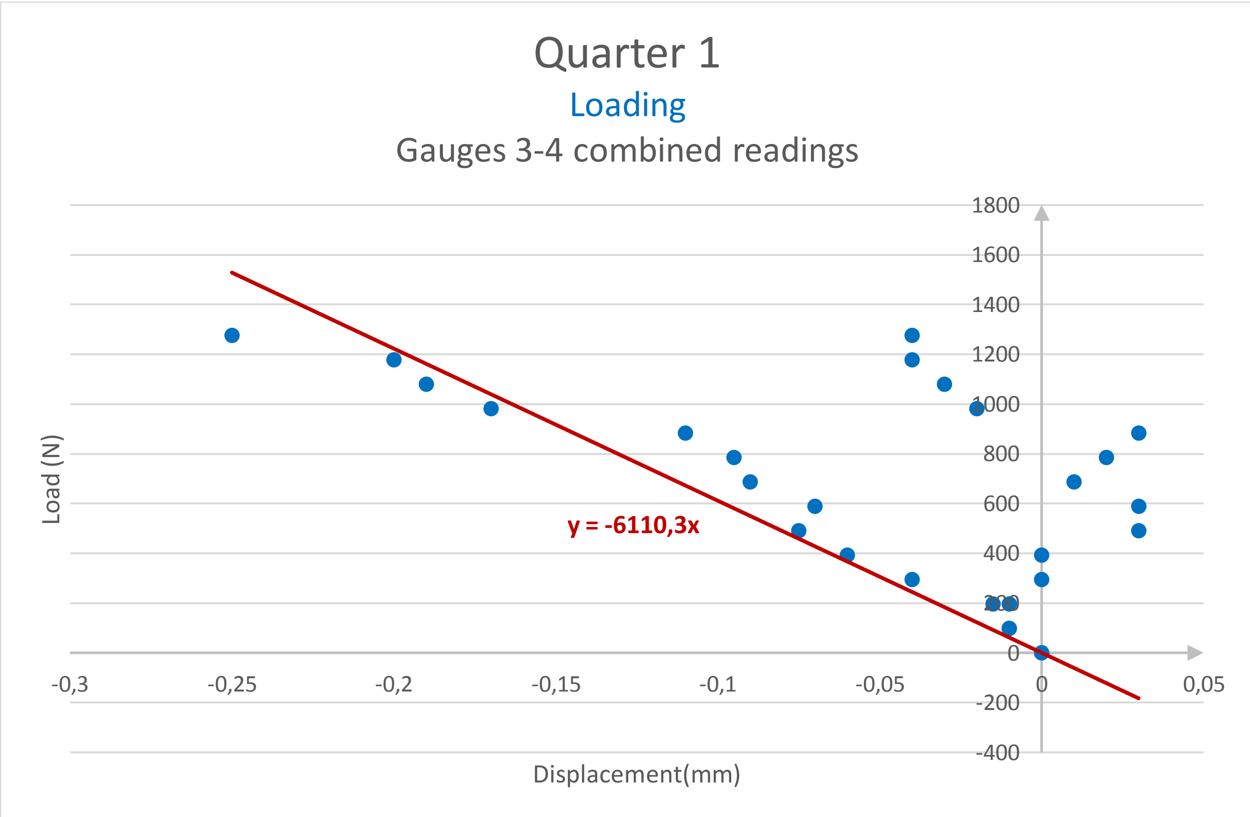









Quarter 1
Loading
Gauges 1-2 combined readings
Load (N)
Displacement(mm)
y = -2355,6x
R² = 0,6422
1800
1600
1400
1200
1000
800
600
400
200
0
-0,7
-0,6
-0,5
-0,4
-0,3
-0,2
-0,1
0


Quarter 1
Loading
Gauges 3-4 combined readings
Load (N)
Displacement(mm)
y = -6110,3x
1800
1600
1400
1200
1000
800
600
400
200
0
-200
-400
-0,3
-0,25
-0,2
-0,15
-0,1
-0,05
0
0,05

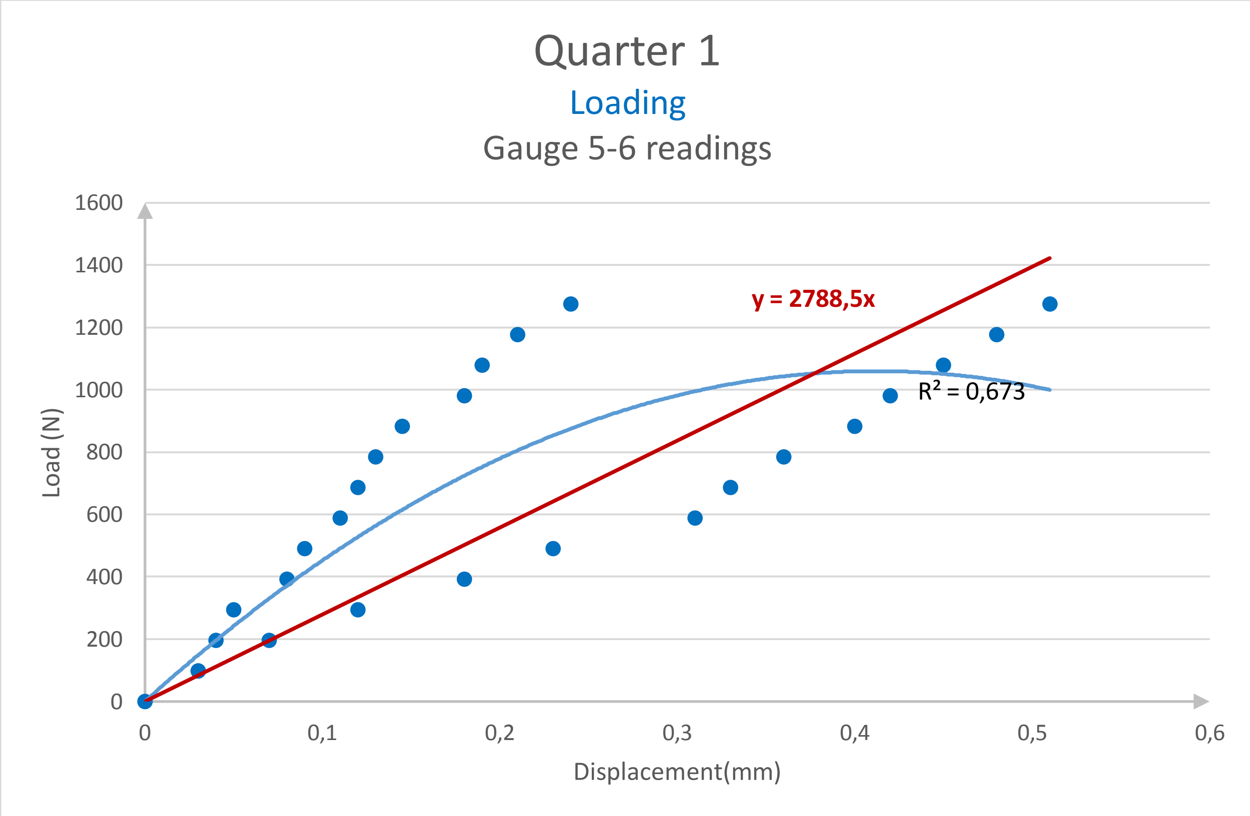


Table C10

Gauge 1		
Displacement (mm)	Point Load (kg)	Total Load (N)
0	0	0
-0,06	2	98,1
-0,09	4	196,2
-0,135	6	294,3
-0,17	8	392,4
-0,225	10	490,5
-0,28	12	588,6
-0,34	14	686,7
-0,38	16	784,8
-0,425	18	882,9
-0,51	20	981
-0,565	22	1079,1
-0,61	24	1177,2
-0,66	26	1275,3
-0,56	21	1030,05
-0,45	16	784,8
-0,34	11	539,55
-0,23	6	294,3
-0,55	0	0

Gauge 2		
Displacement (mm)	Point Load (kg)	Total Load (N)
0	0	0
-0,035	2	98,1
-0,05	4	196,2
-0,06	6	294,3
-0,05	8	392,4
-0,075	10	490,5
-0,07	12	588,6
-0,08	14	686,7
-0,08	16	784,8
-0,12	18	882,9
-0,21	20	981
-0,25	22	1079,1
-0,29	24	1177,2
-0,35	26	1275,3
-0,25	21	1030,05
-0,175	16	784,8
-0,11	11	539,55
-0,11	6	294,3
-0,03	0	0

Gauge 3		
Displacement (mm)	Point	Total

Gauge 4		
Displacement (mm)	Point	Total

	Load (kg)	Load (N)
0	0	0
-0,01	2	98,1
-0,015	4	196,2
-0,04	6	294,3
-0,06	8	392,4
-0,075	10	490,5
-0,07	12	588,6
-0,09	14	686,7
-0,095	16	784,8
-0,11	18	882,9
-0,17	20	981
-0,19	22	1079,1
-0,2	24	1177,2
-0,25	26	1275,3
-0,2	21	1030,05
-0,14	16	784,8
-0,1	11	539,55
-0,04	6	294,3
-0,02	0	0

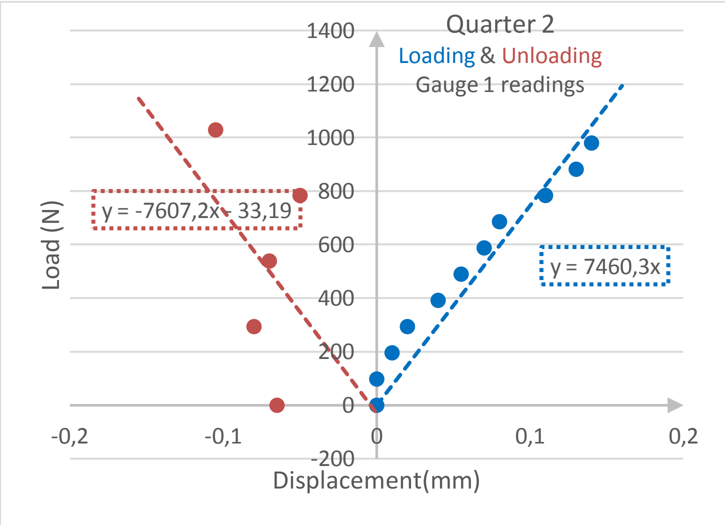
	Load (kg)	Load (N)
0	0	0
-0,01	2	98,1
-0,01	4	196,2
0	6	294,3
0	8	392,4
0,03	10	490,5
0,03	12	588,6
0,01	14	686,7
0,02	16	784,8
0,03	18	882,9
-0,02	20	981
-0,03	22	1079,1
-0,04	24	1177,2
-0,04	26	1275,3
-0,215	21	1030,05
0,05	16	784,8
0	11	539,55
-0,05	6	294,3
0,02	0	0

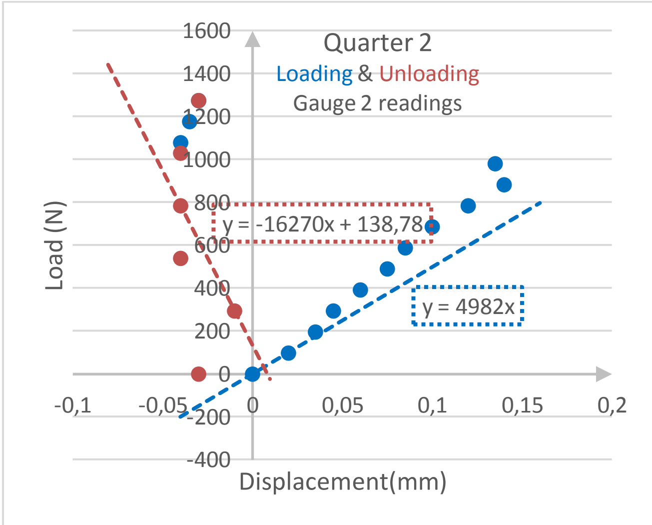
Gauge 5		
Displacement (mm)	Point Load (kg)	Total Load (N)
0	0	0
0,03	2	98,1
0,04	4	196,2
0,05	6	294,3
0,08	8	392,4
0,09	10	490,5
0,11	12	588,6
0,12	14	686,7
0,13	16	784,8
0,145	18	882,9
0,18	20	981
0,19	22	1079,1
0,21	24	1177,2
0,24	26	1275,3
0,19	21	1030,05
0,11	16	784,8
0,08	11	539,55
0,02	6	294,3
-0,01	0	0

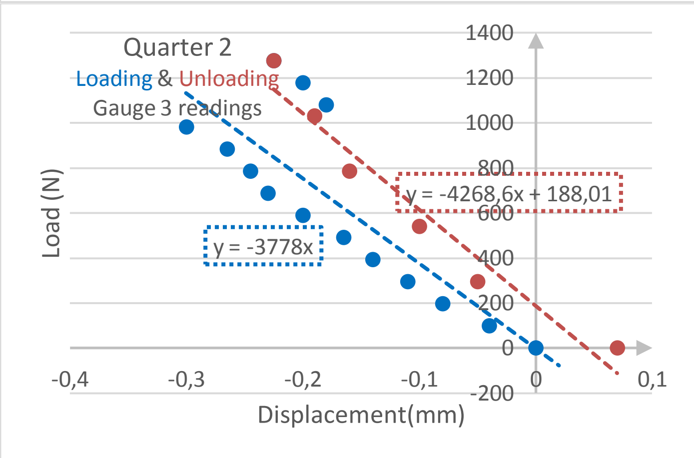
Gauge 6		
Displacement (mm)	Point Load (kg)	Total Load (N)
0	0	0
0,03	2	98,1
0,07	4	196,2
0,12	6	294,3
0,18	8	392,4
0,23	10	490,5
0,31	12	588,6
0,33	14	686,7
0,36	16	784,8
0,4	18	882,9
0,42	20	981
0,45	22	1079,1
0,48	24	1177,2
0,51	26	1275,3
0,44	21	1030,05
0,39	16	784,8
0,3	11	539,55
0,22	6	294,3
0,1	0	0

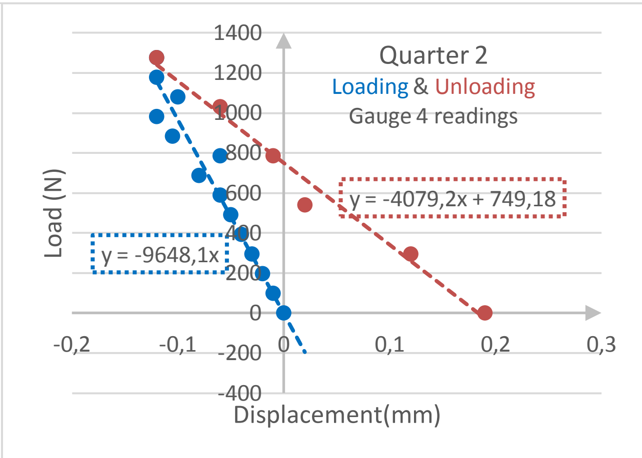
QUARTER 2 LOADING

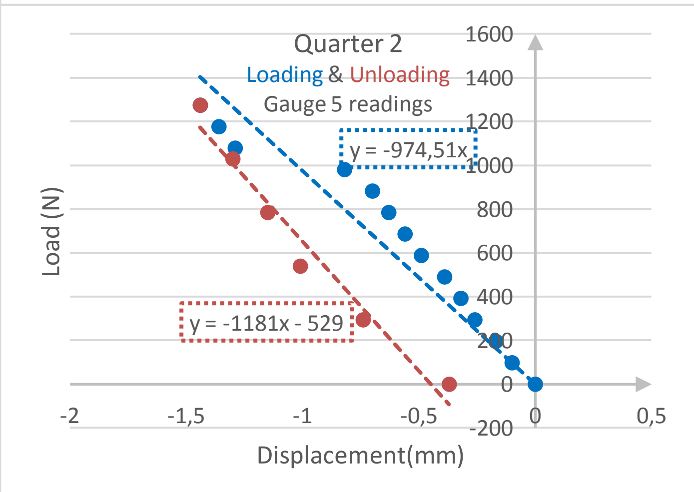
Table C11

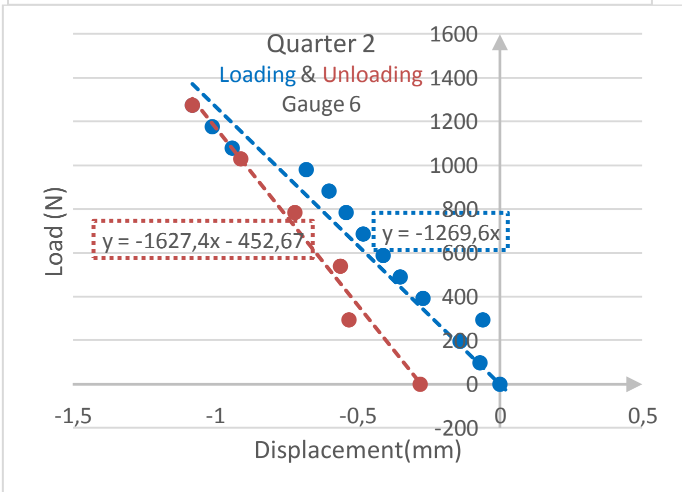


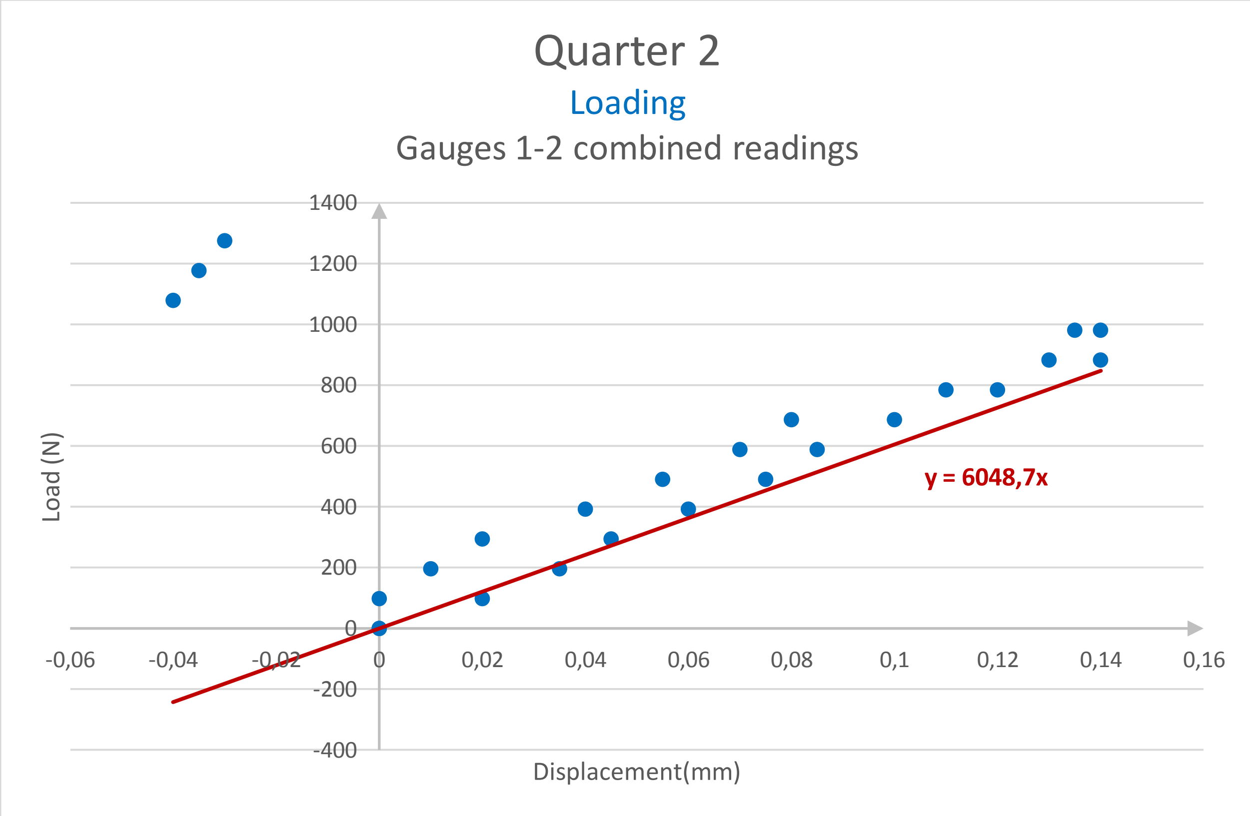




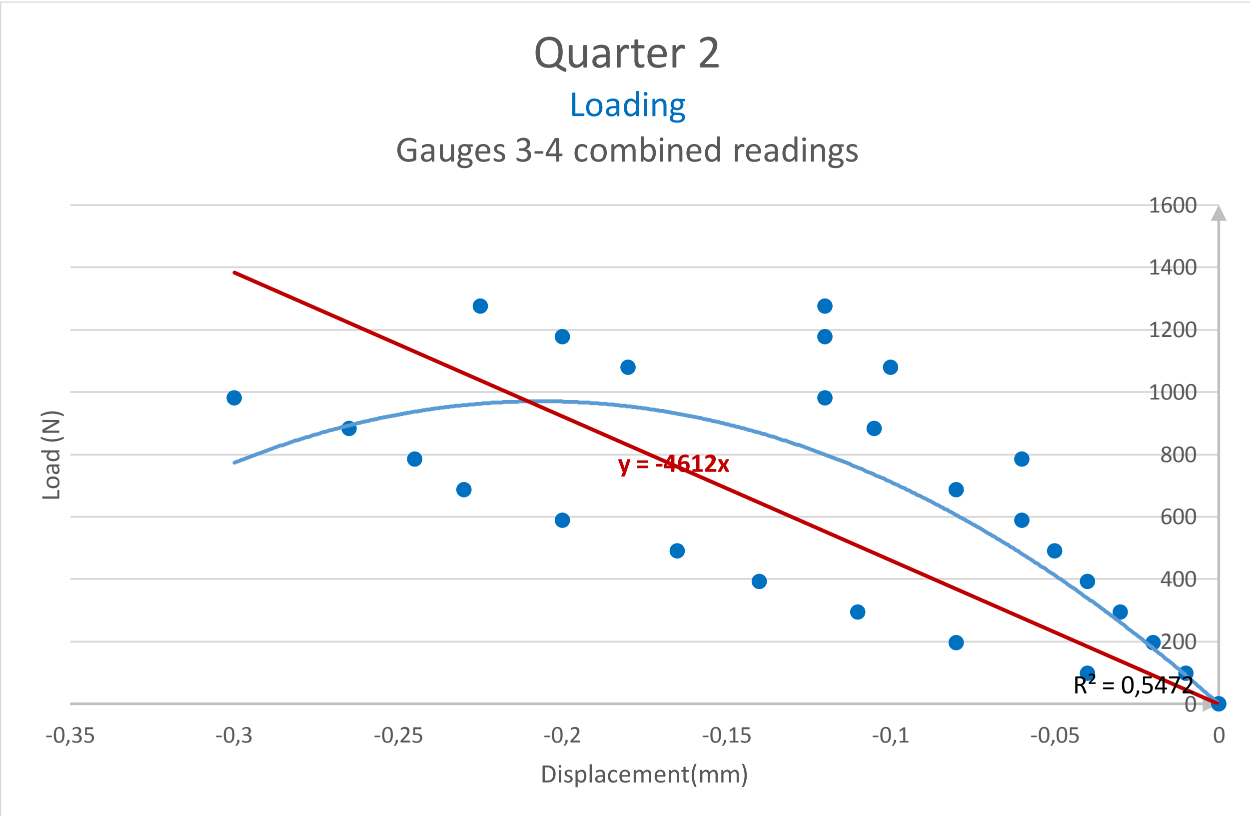








Quarter 2
Loading
Gauges 1-2 combined readings
Load (N)
Displacement(mm)
y = 6048,7x



Quarter 2
Loading
Gauges 3-4 combined readings
Load (N)
Displacement(mm)
y = -4612x
R^2 = 0,5472

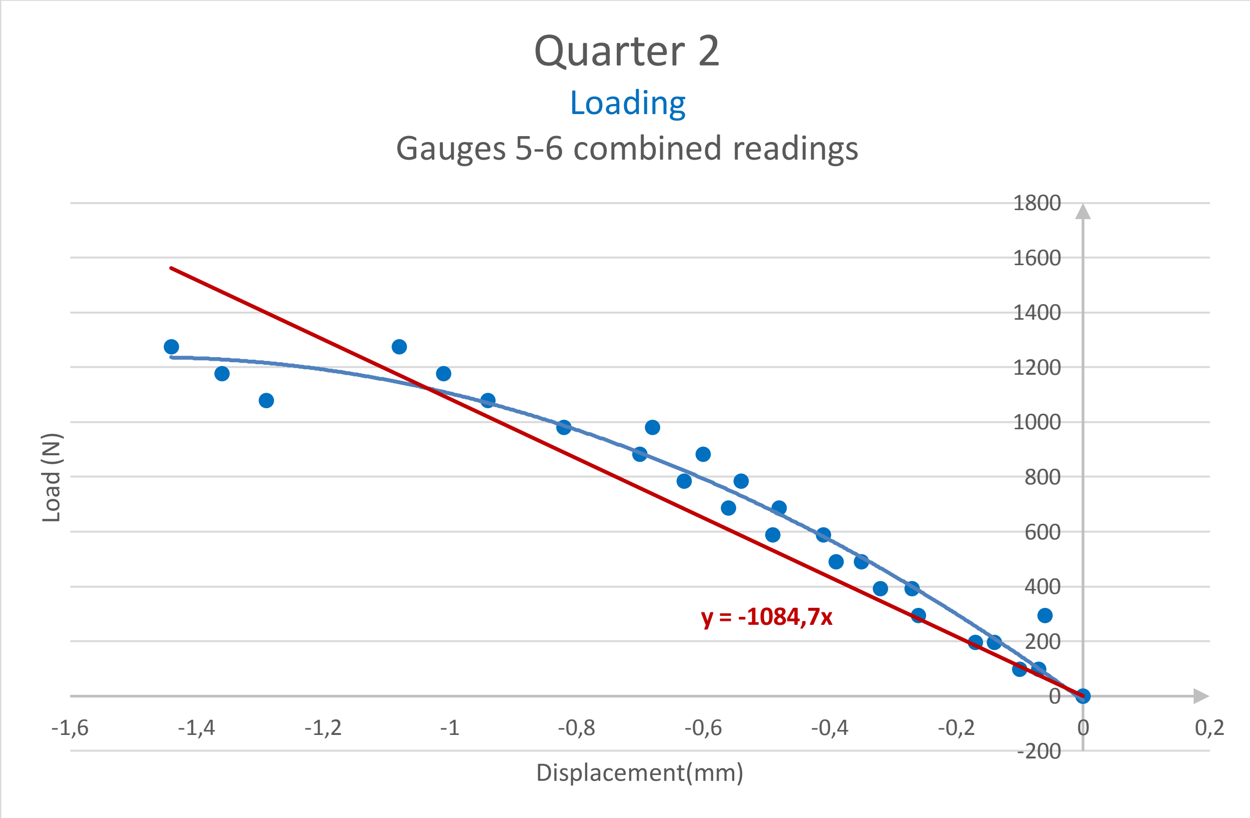


Table C12

Gauge 1		
Displacement (mm)	Point Load (kg)	Total Load (N)
0	0	0
0	2	98,1
0,01	4	196,2
0,02	6	294,3
0,04	8	392,4
0,055	10	490,5
0,07	12	588,6
0,08	14	686,7
0,11	16	784,8
0,13	18	882,9
0,14	20	981
-0,105	21	1030,05
-0,05	16	784,8
-0,07	11	539,55
-0,08	6	294,3
-0,065	0	0

Gauge 2		
Displacement (mm)	Point Load (kg)	Total Load (N)
0	0	0
0,02	2	98,1
0,035	4	196,2
0,045	6	294,3
0,06	8	392,4
0,075	10	490,5
0,085	12	588,6
0,1	14	686,7
0,12	16	784,8
0,14	18	882,9
0,135	20	981
-0,04	22	1079,1
-0,035	24	1177,2
-0,03	26	1275,3
-0,04	21	1030,05
-0,04	16	784,8
-0,04	11	539,55
-0,01	6	294,3
-0,03	0	0

Gauge 3

Gauge 4

Displacement (mm)	Point Load (kg)	Total Load (N)
0	0	0
-0,04	2	98,1
-0,08	4	196,2
-0,11	6	294,3
-0,14	8	392,4
-0,165	10	490,5
-0,2	12	588,6
-0,23	14	686,7
-0,245	16	784,8
-0,265	18	882,9
-0,3	20	981
-0,18	22	1079,1
-0,2	24	1177,2
-0,225	26	1275,3
-0,19	21	1030,05
-0,16	16	784,8
-0,1	11	539,55
-0,05	6	294,3
0,07	0	0

Displacement (mm)	Point Load (kg)	Total Load (N)
0	0	0
-0,01	2	98,1
-0,02	4	196,2
-0,03	6	294,3
-0,04	8	392,4
-0,05	10	490,5
-0,06	12	588,6
-0,08	14	686,7
-0,06	16	784,8
-0,105	18	882,9
-0,12	20	981
-0,1	22	1079,1
-0,12	24	1177,2
-0,12	26	1275,3
-0,06	21	1030,05
-0,01	16	784,8
0,02	11	539,55
0,12	6	294,3
0,19	0	0

Gauge 5		
Displacement (mm)	Point Load (kg)	Total Load (N)
0	0	0
-0,1	2	98,1
-0,17	4	196,2
-0,26	6	294,3
-0,32	8	392,4
-0,39	10	490,5
-0,49	12	588,6
-0,56	14	686,7
-0,63	16	784,8
-0,7	18	882,9
-0,82	20	981
-1,29	22	1079,1
-1,36	24	1177,2
-1,44	26	1275,3
-1,3	21	1030,05
-1,15	16	784,8
-1,01	11	539,55
-0,74	6	294,3
-0,37	0	0

Gauge 6		
Displacement (mm)	Point Load (kg)	Total Load (N)
0	0	0
-0,07	2	98,1
-0,14	4	196,2
-0,06	6	294,3
-0,27	8	392,4
-0,35	10	490,5
-0,41	12	588,6
-0,48	14	686,7
-0,54	16	784,8
-0,6	18	882,9
-0,68	20	981
-0,94	22	1079,1
-1,01	24	1177,2
-1,08	26	1275,3
-0,91	21	1030,05
-0,72	16	784,8
-0,56	11	539,55
-0,53	6	294,3
-0,28	0	0

APPENDIX D: COLLAPSE LOAD TESTING

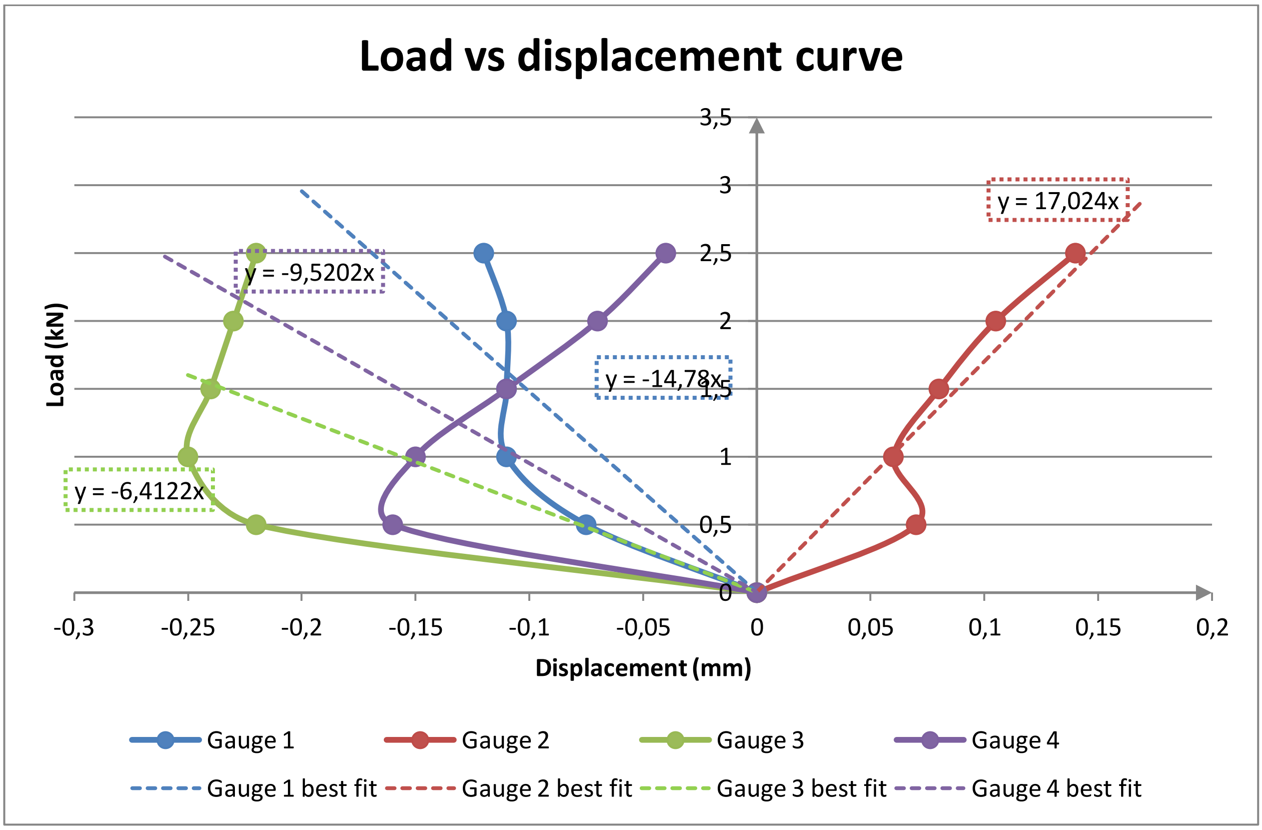


Figure D1. Shell 2: Load-displacement curves excluding displacements beyond collapse load. Best fitting lines with the origin at (0,0).

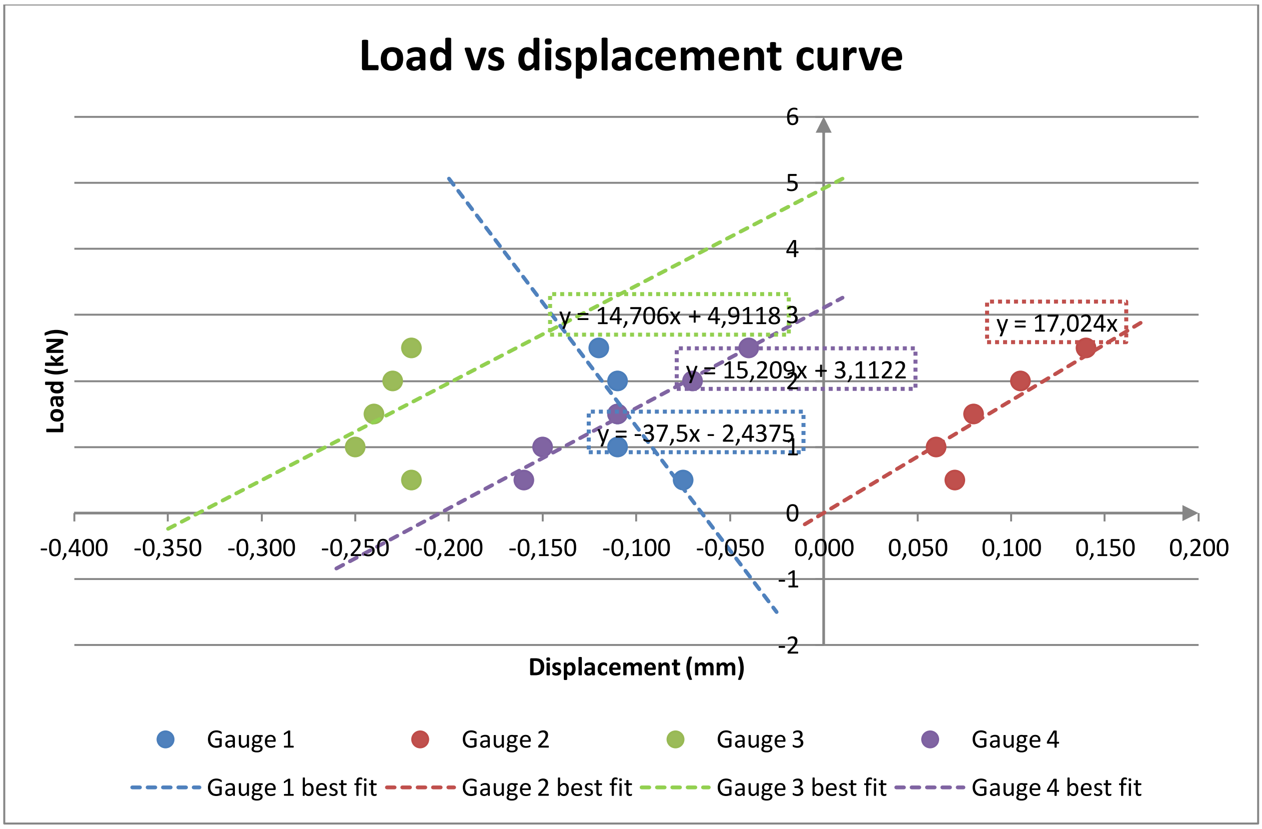


Figure D2. Shell 2: Load-displacement curves excluding displacements beyond collapse load. The origin of the best fitting lines not specified.